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LEVEL II

1

PERFORMANCE CHARACTERISTICS
OF
CLUSTERED NOZZLES

AFIT/GAE/AA/81D-14

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PERFORMANCE CHARACTERISTICS OF CLUSTERED NOZZLES

THESIS

Presented to the Faculty of the School of Engineering
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Requirements for the Degree of
Master of Science

by
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Preface

In this report, I have attempted to present the reader with an easily understood report on the evaluation of thrust coefficient for clustered nozzles.

This thesis represents a summary of various concepts that I have learned about clustering nozzles. Although a thesis is important to the research and scientific world, I feel that my experiences and achievements exceeded the ideas contained within these pages. During this 18 month period, I have had the opportunity and pleasure of having a new friend. As a thesis advisor, Dr. W. C. Elrod has given of himself unselfishly. He has always had an ear to lend and has offered alternative and valuable solutions to various problems both on the professional and personal level. I have thoroughly enjoyed working with and having Dr. Elrod as my advisor during the course of this study.

I wish to acknowledge my love and appreciation to my wife, Kathy. Throughout this study, I have tormented her with a sporadic meal schedule, a never ending laundry pile, and a mind plagued with engineering problems. Yet she endured each day by handing me a beer and telling me she understood. Also, a special thanks to our dog Clyde who greeted me each day with a friendly wag. When things didn't go well during the course of this study, as they often didn't, Clyde would approach with a ball to be thrown or with a leash for a walk in the park. Mostly, I thank them both for showing me in their

own way that John Lennon was right when he said, "All you need is love."

A very special thanks to Dr. P. Torvik for his assistance with the visicorder and instrumentation. Professor Torvik made numerous and valuable suggestions in setting up and debugging the instrumentation. I thank him for taking a personal interest in this study.

Many others have contributed to this study over the past year. I would like to take the time to thank a few of them now.

-Dr. H. Wright and Dr. M. Franke, my thesis committee, for their suggestions throughout the course of this study.

-Mr. Shortt and Mr. Brohas, from the fabrication shop, for their handiwork in developing and building of the apparatus.

-Mr. Baker and Mr. Cannon, the lab technicians, for their assistance in the assembling of the apparatus.

-Ms. K. Newman, personal friend, for her assistance with the viewgraphs.

David V. Hibson

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A_t nozzle throat area (in^2)

A_2 nozzle exit area (in^2)

C_f thrust coefficient

C_{f_m} measured thrust coefficient

C_{f_t} theoretical thrust coefficient

D diameter of mass flow meter (in)

d diameter of orifice (in)

$g_c = 32.174$ (ft lb_m)/(lb_f s^2)

M_e exit Mach number

m mass flow rate (lb_m/s)

$P_r = \frac{p_1}{p_3}$

p_a ambient pressure (Hg)

p_1 chamber pressure (psia)

p_2 pressure at exit plane of nozzle (psia)

p_3 ambient pressure (psia)

R nozzle throat radius (in)

r nozzle exit plane radius (in)

T thrust (lb_f)

T_m measured thrust (lb_f)

List of Symbols

T_t theoretical thrust (lb_f)

V_2 velocity of gas at exit plane of nozzle (fps)

X divergent length of nozzle (in)

$\beta = d/D$

Abstract

This is an experimental evaluation of the thrust performance of 3 sets of clustered, three-dimensional, converging-diverging, cold flow, supersonic nozzles. A cluster of 2,4, and 6 nozzles were designed and fabricated. Each cluster assembly has the same geometry in that their area ratio, expansion ratio, and total throat area is the same. A single nozzle with the same geometry and total throat area was used to evaluate the creditability of the testing procedure and the performance of the 3 sets of clustered nozzles. The thrust performance of each nozzle cluster was evaluated by comparison of the measured thrust coefficient of the cluster to that of a single nozzle. The nozzle with the highest thrust coefficient was the cluster of 2 nozzles. Its performance was closely followed by the cluster of 4 nozzles. The nozzle with the lowest thrust coefficient was the cluster of 6 nozzles. The results of this study indicate that the clustering of nozzles improves the thrust performance.

PERFORMANCE CHARACTERISTICS OF CLUSTERED NOZZLES

I. Introduction

The concept of clustering arrays of rocket engines is not new. In the early 60's nozzles were clustered in order to capitalize on the altitude compensating characteristics of plug nozzles. Recent work has been aimed at achieving high vacuum specific impulse by clustering existing rocket engines to for very high area ratio engines. A specific application now being considered at AFRPL, Edwards AFB, California, is the clustering of existing modules such as the RL-10 O_2/H_2 engine. No information is presently available on the performance of clustered nozzles of this type at the high pressure ratios characteristic of these rocket engines (ref 6).

The object of this thesis was.

1. To design, fabricate, and calibrate the necessary apparatus and instrumentation in order to determine the thrust coefficient for single and clustered nozzles.
2. To experimentally determine the thrust performance and stability of operation of 3 sets of clustered, three-dimensional, converging-diverging, cold flow, supersonic nozzles.

This is an experimental study in model scale. In this study, a clustered nozzle assembly is considered to be 2 or more nozzles that are held together and have equivalent throat areas. Determination of the relative thrust efficiency of each nozzle set was accomplished by comparison of its thrust coefficient to that of a single nozzle whose throat area was the same as that of the total throat area of the set.

II. Theory

An objective of this study was to investigate experimentally the thrust performance of clustered nozzles in model scale. The thrust performance of each nozzle cluster was evaluated by comparing it to a standard single nozzle by comparing their respective measured thrust coefficient. The thrust coefficient determines "the amplification of thrust due to the gas expansion in the rocket nozzle as compared to the thrust that would be exerted if the chamber pressure acted over the throat area only" (ref 5). Thrust coefficient may be defined as:

$$C_f = \frac{T}{A_t p_1}$$

By use of conservation momentum, the thrust is equal to (ref 5):

$$T = \dot{m}V_2 + (p_2 - p_3)A_2$$

"The thrust is composed of two terms. The first term, the momentum thrust, is the product of the gas (propellant) mass flow rate and the exhaust velocity relative to the nozzle (vehicle). The second term, the pressure thrust, consists of the product of the cross-sectional area of the exhaust jet leaving the nozzle and the difference between the exhaust pressure and the fluid pressure. If the exhaust presure is less than the surrounding fluid pressure, the pressure thrust is negative" (ref 5). This condition is known as overexpansion and is undesirable due to the loss in thrust.

An underexpanding nozzle discharges the gas at a pressure greater than the ambient pressure. In this case, the nozzle exit, area is too small. A nozzle with optimum expansion is when the nozzle exit pressure is equal to the ambient pressure. At this condition, the thrust, and therefore the thrust coefficient also, is at a maximum.

The effect of either overexpansion or underexpansion is a slight reduction in the exhaust velocity and, therefore, a loss in energy. The loss of thrust due to overexpansion and underexpansion may be determined from the thrust coefficient. This theory assumes that the nozzle is flowing full (i.e. $p_2 \geqq 0.4p_3$) and that the pressure thrust is positive for underexpansion and negative for overexpansion. For under-expansion and for slight overexpansion, this simple theory is in accurate agreement with measured results.

A sample calculation may be found in Appendix C. The sample calculation gives rise to the desired quantities to be measured. Knowing the desired quantities, the first objective, design, fabricate, and check the apparatus, was then achieved.

III. Apparatus

The purpose of the apparatus was to provide a means to obtain the necessary data to determine the thrust coefficient for the nozzle clusters. The theory section indicated the various quantities needed to be measured (i.e. pressure, temperature, thrust). From this, the first objective, to design and build an apparatus, was completed.

The experimental apparatus consisted of a nozzle cluster assembly, stilling chamber, mass flow meter, visicorder, and various regulating valves and hardware. Descriptions of each and its use in this study are given below. A schematic is shown in Fig. 1. Further details and drawings may be found in Appendix B.

Nozzle Cluster Assembly

The nozzles were designed and then fabricated from aluminum stock (Fig 3). The nozzles were designed using one-dimensional isentropic relations (ref 2) for a pressure ratio of $\frac{P_3}{P_1} = 0.04711$ ($M_e = 2.64$). Each nozzle inlet was designed using a constant arc of radius 1.837 ± 0.001 in (ref 3).

The 3 sets of nozzle clusters were designed with the same total throat area. A cluster of 2, 4, and 6 nozzles were assembled. The cluster arrangements are shown in Fig 4. Each nozzle was machined separately and then fastened to an aluminum base plate. Clay was used to seal the seamlines between the nozzles. For control purposes (see test procedure section), a single nozzle with the same geometry and total

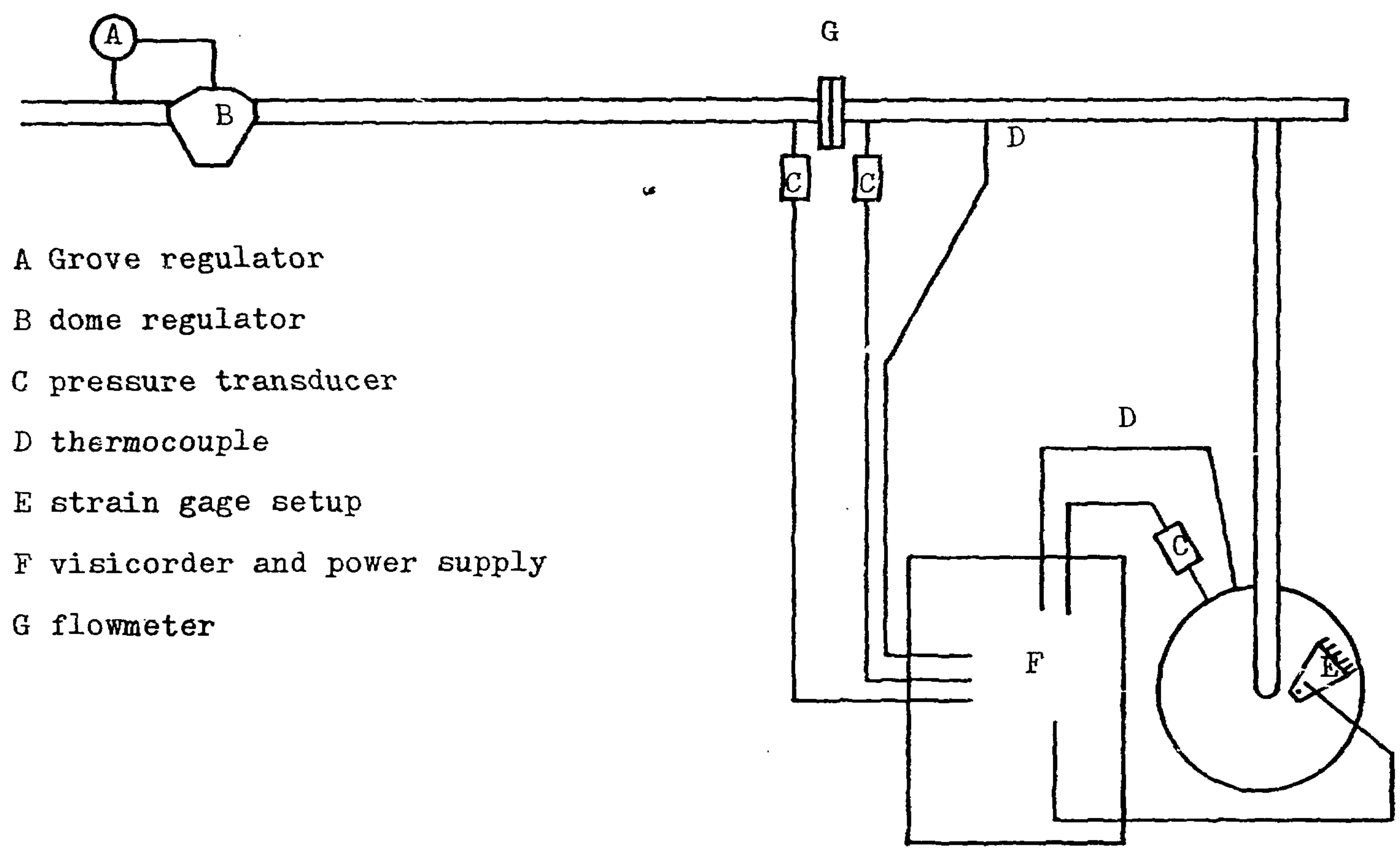


Fig 1 Apparatus Setup

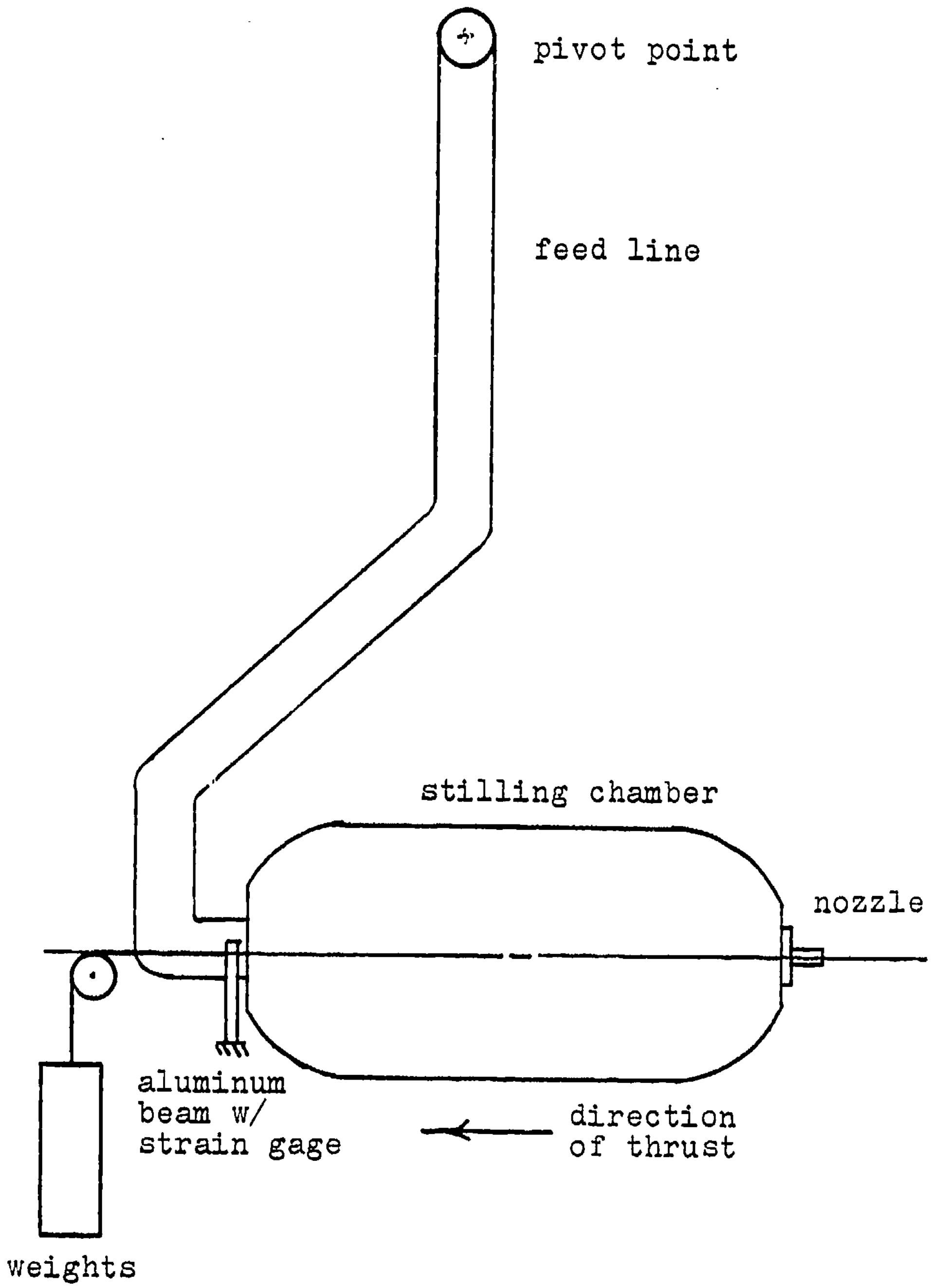


Fig 2 Thrust Measuring Setup

throat area was made. Also, a spare nozzle from each cluster assembly was fabricated. This made a total of 7 nozzles, that is 3 cluster nozzle assemblies, a large single nozzle, and 3 more single nozzles from each cluster.

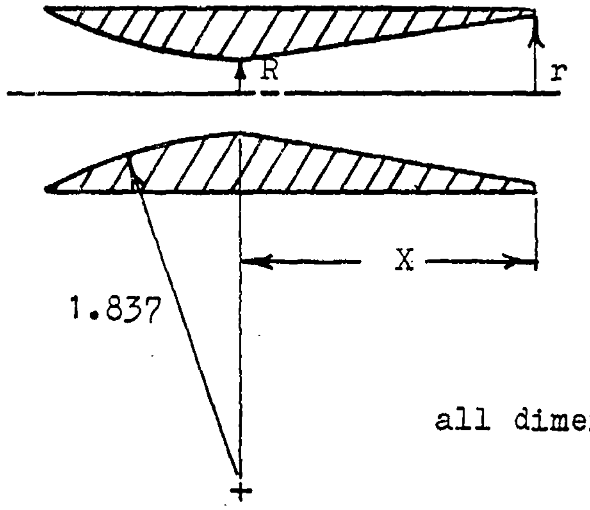
Stilling Chamber

The nozzle base plate fastened directly to the stilling chamber. The chamber provided a reservoir of compressed air. Within the stilling chamber, a basket-type diffuser (Fig B-1) disseminated the incoming gas in a radial direction to the stilling chamber. The nozzles were tested at a chamber pressure of 150, 200, 250, 300, and 350 psig.

The stilling chamber pivoted via its 5 ft long feed line as shown in Fig 2. At the pivot point, the inner slotted tube diffused the gas in a radial direction before the gas entered the feed line. Bearings and O-rings were used to reduce friction and provide a proper seal (Fig B-2). Strain gages mounted on an aluminum beam were used to measure the thrust created by the nozzle assembly (Fig 2). A pressure transducer and a thermocouple measured the pressure and temperature of the gas respectively.

Mass Flow Meter

A thin-plate square edge orifice meter, built and installed according to ASME standards, was located just prior to the stilling chamber assembly (Fig 1). The mass flow meter was designed using the energy equation (ref 1) for a diameter ratio of $\beta = \frac{1}{2}$ (Fig B-3). Two pressure transducers and a thermocouple measured the pressure and temperature of the gas.



all dimensions in inches

Nozzle	R	A_t	r	X
1	0.307	0.2945	0.5303	2.241
2	0.222	0.1472	0.3749	1.584
3	0.153	0.0736	0.2650	1.119
4	0.127	0.0491	0.2165	0.915

Fig 3 Nozzle Design

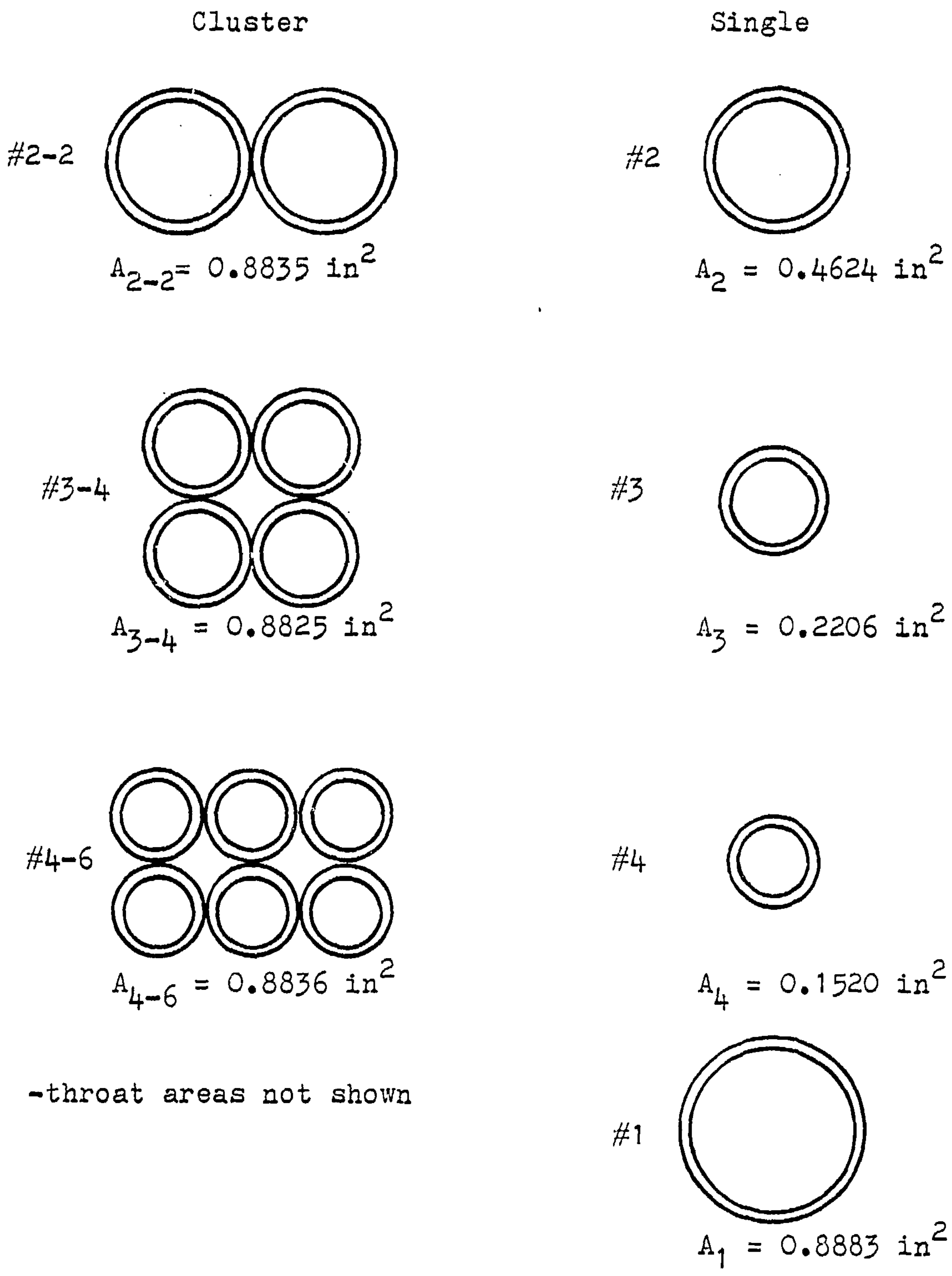


Fig 4 Nozzle Exit Area Configurations

Visicorder

A Honeywell visicorder, model 1508, was used to record all data. The voltage outputs from the various pressure tranducers, thermocouples, and thrust measuring device were each wired independently to one of the 8 channels to the visicorder. Of the 8 channels used, the thrust data was recorded on 1 of 3 channels. The thrust measuring channel was selected according to the nozzle being tested (see test procedure).

Regulating Valves and Hardware

A Grove regulating valve was used to adjust the pressure above the diaphram in the dome regulator. The dome regulator then adjusted the air pressure from the supply line pressure to the desired operating pressure. Air was supplied from a nearby trailer unit.

After the apparatus was completed, the instrumentation was calibrated and test procedures were established as described next.

IV. Test Procedure

With the experimental apparatus assembled, the last part of objective 1, to calibrate the instrumentation and to provide a test procedure for the apparatus, was completed. Nozzles 1 thru 4 were used as a standard to calibrate and de-bug the system. A description of how the mass flow meter, thrust measuring device, pressure transducers and thermocouples, and visicorder were calibrated are given below.

Mass Flow Meter

The mass flow meter was designed and installed according to ASME standards (ref 1). No direct calibration was required. Various equations and charts (see ref 1 and Appendix C) were used to determine the mass flow rate. As a check, isentropic conditions were assumed at the nozzle throat to determine a second calculation of mass flow rate. The 2 mass flow rates were used in the results section.

Thrust Measuring Device

The thrust measuring device was an aluminum beam with mounted strain gages as shown in Fig 2. The thrust is measured along the centerline of the stilling chamber and the nozzle. This design restricted the movement of the stilling chamber to 5/32 in and thereby reduced unnecessary friction from the O-ring assembly at the pivot point. To further reduce this effect, the stilling chamber was vibrated during the data collecting period. This method reduced friction effects to a minimum.

A similar problem was encountered during the calibration of the thrust measuring device. Weights were suspended from the device via a basket, cable and pulley assembly (Fig 2). Again the stilling chamber was vibrated to reduce frictional effects from the pulley assembly.

This study does not concern itself with the exact effects of the friction incurred from the calibration and test procedures on the data. Nozzle 1 was tested to indicate if the hysterisis effects were indeed negligible (Fig A-11). A correlation factor was found for the thrust data taken and indicated that the data was linear. Knowing that the measured thrust data obtained is linear, hysterisis from frictional effects was assumed negligible in the testing procedure.

Pressure Transducers and Thermocouples

Pressure transducers were calibrated by use of a dead weight tester. Two iron vs constantan thermocouples were used to measure the gas temperature. They were calibrated by inserting the thermocouple bead into a water bath with a thermometer, heating it, and recording the visicorder reading and the thermometer reading.

Visicorder

All measuring devices fed their voltage outputs directly to the visicorder. The visicorder recorded all inputs on a light sensitive graph paper. All data was recorded within the 20 cm width of paper. In order to provide the proper resolution, the thrust measuring device was required to record on 3 separate channels. One channel for thrust 0 - 35 lb_f, another for 25-85 lb_f, and the third for 40 - 150 lb_f provided the data to be resolved to within 2.0% of its recorded value.

All inputs to the visicorder, with the exception of the thermocouples, used a variable resistor as indicated in Fig B-4. The variable resistor provided 2 useful functions. First, it permitted the entire recording space to be used. An example of this is the pressure transducer for the stilling chamber. Tests were made between 150 - 350 psig. Therefore, the 1 cm mark was the 150 psig point and the 19 cm mark was the 350 psig point. This permitted the best attainable resolution in the recorded data and also kept the galvanometer well within its linear range. Second, the variable resister permitted an easy method to calibrate the readings from day to day. An example of this would be to place a 15 lb_f on the thrust measuring device. The variable resistor could then be adjusted, if necessary, to locate the light beam at the proper point. In addition, the variable resistor did not change the sensitivity of the galvanometer.

<u>Procedure</u>

A nozzle assembly was selected and fastened to the rear of the stilling chamber (Fig 2). The Grove regulator was then adjusted to increment the gas pressure in the stilling chamber from 150 - 350 psig and back to 150 psig in 50 psig increments. The apparatus was vibrated to reduce frictional effects. This method produced data with a high degree of repeatability as the results section indicates next.

V. Results and Discussion

The apparatus was designed, fabricated, and checked out with the testing of nozzle 1. The single nozzle thrust performance was compared to theory (Fig A-11) in order to establish a base line. A statistical package within the AFIT computer system was used to fit the best curve to the measured and theoretical data. A linear curve was fitted to the measured thrust data points. A correlation factor of 0.9996 indicated that the line fitted to these points was nearly an ideal fit. Knowing that the measured data points were linear, it was assumed that any hysterisis effects encountered in the calibration procedures would have little effect in the data collecting procedures. From the thrust measurements, the thrust coefficient was determined (Fig A-4). Various statistical packages within the computer system were used to fit polynomial curves to the data. Nozzle 1 established a baseline upon which the 3 nozzle cluster sets and their respective standards were evaluated.

A typical graph of the thrust coefficient vs pressure ratio is shown in Fig 5. Graphs of all measurements may be found in Appendix A. A sample calculation with an error analysis may be found in Appendix C. Table I shows the order of best performing nozzles at optimum expansion, $P_r = 21.13$. The equations derived by the computer may be found at the end of Appendix A. The theory curve in Fig 5, and A-1 thru A-3 was found by using the theoretical data points for all

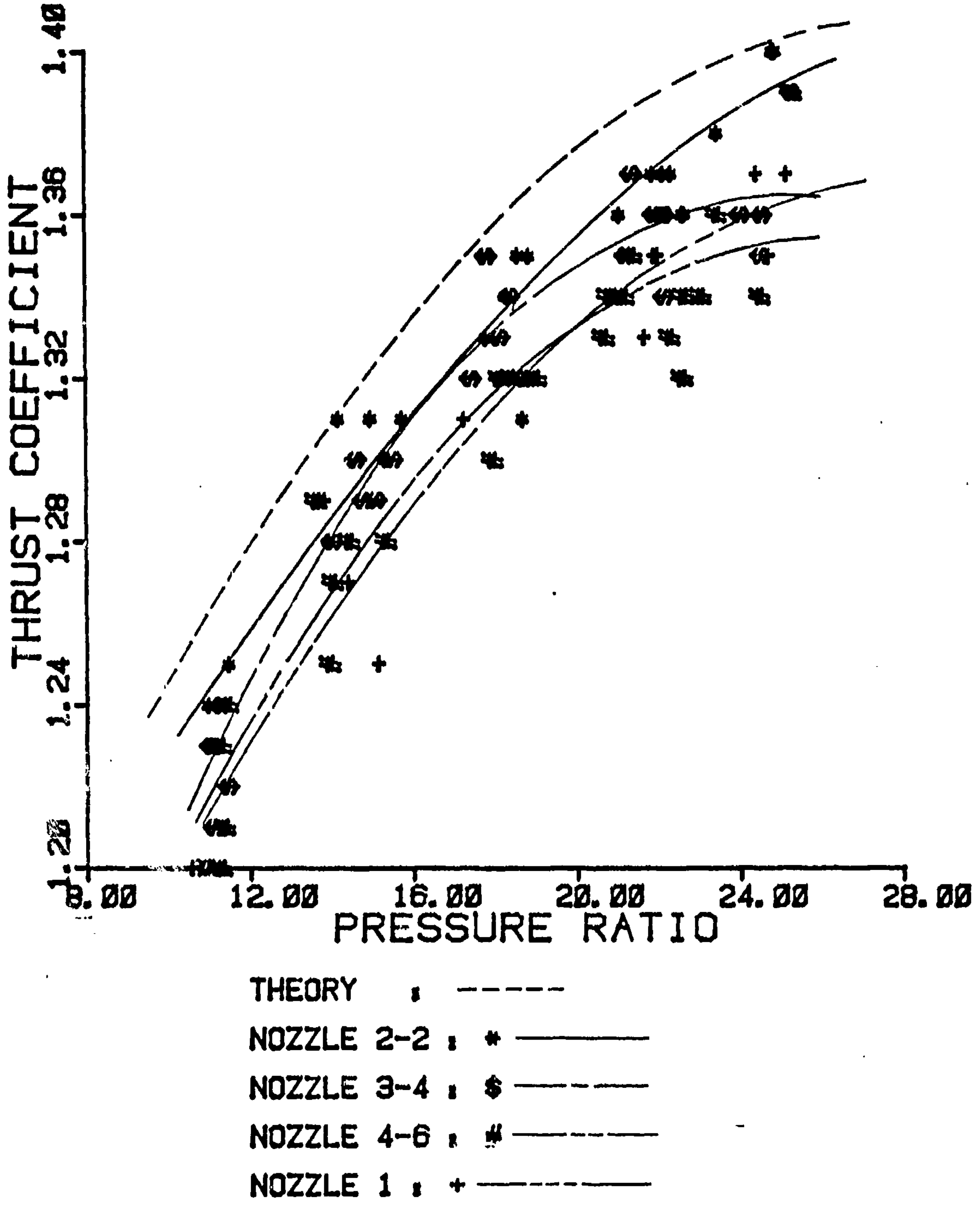


FIG 5 : CLUSTERED AND SINGLE NOZZLES

the nozzles in that particular graph. This resulted in slightly different equation (due to 0.7% difference in A_t) as shown in Table A-2.

Comparison of Cluster Sets with Single Nozzle

A comparison of the 3 cluster nozzle sets with a single nozzle of equivalent throat area is shown in Fig 5. From the calculations in appendix C, the optimum expansion point is at $P_r = 21.13$. A pressure ratio less than 21.13 operates the nozzle at an overexpanded condition while pressure ratios greater than 21.13 operate the nozzle at an underexpanded condition. Nozzle 2-2 has a 1.6% increase in thrust compared to the single nozzle at $P_r = 21.13$. Similarly, nozzle 3-4 has a 1.0% increase in thrust. Nozzle 4-6 was slightly less than the single nozzle by -0.2%. Overall, for all pressure ratios, nozzle 2-2 was the best performer.

Comparison of Nozzle 2-2 with Nozzle 2

Nozzle 2-2 is compared with nozzle 2 in Fig A-1. At a $P_r = 21.13$, nozzle 2-2 has a 2.2% increase in thrust over nozzle 2. For all pressure ratios, nozzle 2-2 out performs nozzle 2.

Comparison of Nozzle 3-4 with Nozzle 3

The results of nozzle 3-4 and nozzle 3 are shown in Fig A-2. Nozzle 3-4 is the best performer. At $P_r = 21.13$, nozzle 3-4 has a 0.7% increase in thrust over nozzle 3.

Comparison of Nozzle 4-6 with Nozzle 4

A graph of the results for nozzle 4-6 and nozzle 4 is shown in Fig A-3. Here, nozzle 4-6 out performs nozzle 4 until a pressure ratio of about 15 is reached, and then the single nozzle 4 performs better than nozzle 4-6. At optimum expansion, nozzle 4 has a 0.7% increase in thrust over nozzle 4-6.

Nozzle 1

The results for nozzle 1 are plotted in Fig A-4. At P_r= 21.13, it is within 3.3% of theoretical results. All nozzles are tabulated in Table I.

Table I. Performance Ratings at Optimum Condition

Nozzle	C_{f_t}	C_{f_m}	$\Delta\%$
2-2	1.38	1.36	1.5
3-4	1.38	1.35	2.4
4	1.39	1.35	2.9
3	1.39	1.35	3.1
1	1.39	1.34	3.3
4-6	1.38	1.34	3.4
2	1.39	1.34	3.5

$$\Delta\,\% = \frac{C_{f_t} - C_{f_m}}{C_{f_m}} * 100\ \%$$

VI. Conclusions

The apparatus and instrumentation was designed, fabricated and check out by the author. From the results section and the error analysis in Appendix C, the data obtained from this study has a high degree of repeatability. The error analysis indicated that the data points should have a spread of $\pm$ 2.0%. The actual data points are contained well within these boundaries. From this, the following conclusion may be drawn:

1. The apparatus is suitable for determining the thrust coefficient for single and clustered nozzles.

A single nozzle was tested and evaluated in order to create a baseline. The 3 sets of clustered nozzles were then compared to the single nozzle. Following this, the 3 nozzle sets and their respective standard nozzles were evaluated. After analyzing the results, the following conclusion may be drawn:

2. The thrust performance does vary with each of the different nozzle configurations. This study suggests that there is a relationship between the number and arrangement of the nozzle exhausts and the free stream flow such that their interaction influences the pressure thrust term in the thrust equation. This study indicates that clustering of nozzles improves thrust performance.

VII. Recommendations

The recommendations arising out of the course of this study are:

1. Further study of clustered nozzles should be performed to examine the effect of shrouding between the nozzles to improve the performance of the 4 and 6 nozzle cluster.

2. Additional study of clustered nozzles of non-convensional shape (i.e. rectangular, oval, etc.) and in various configurations could be completed to provide a data base for future design work.

3. Continue this study using higher pressure ratios.

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Appendix A

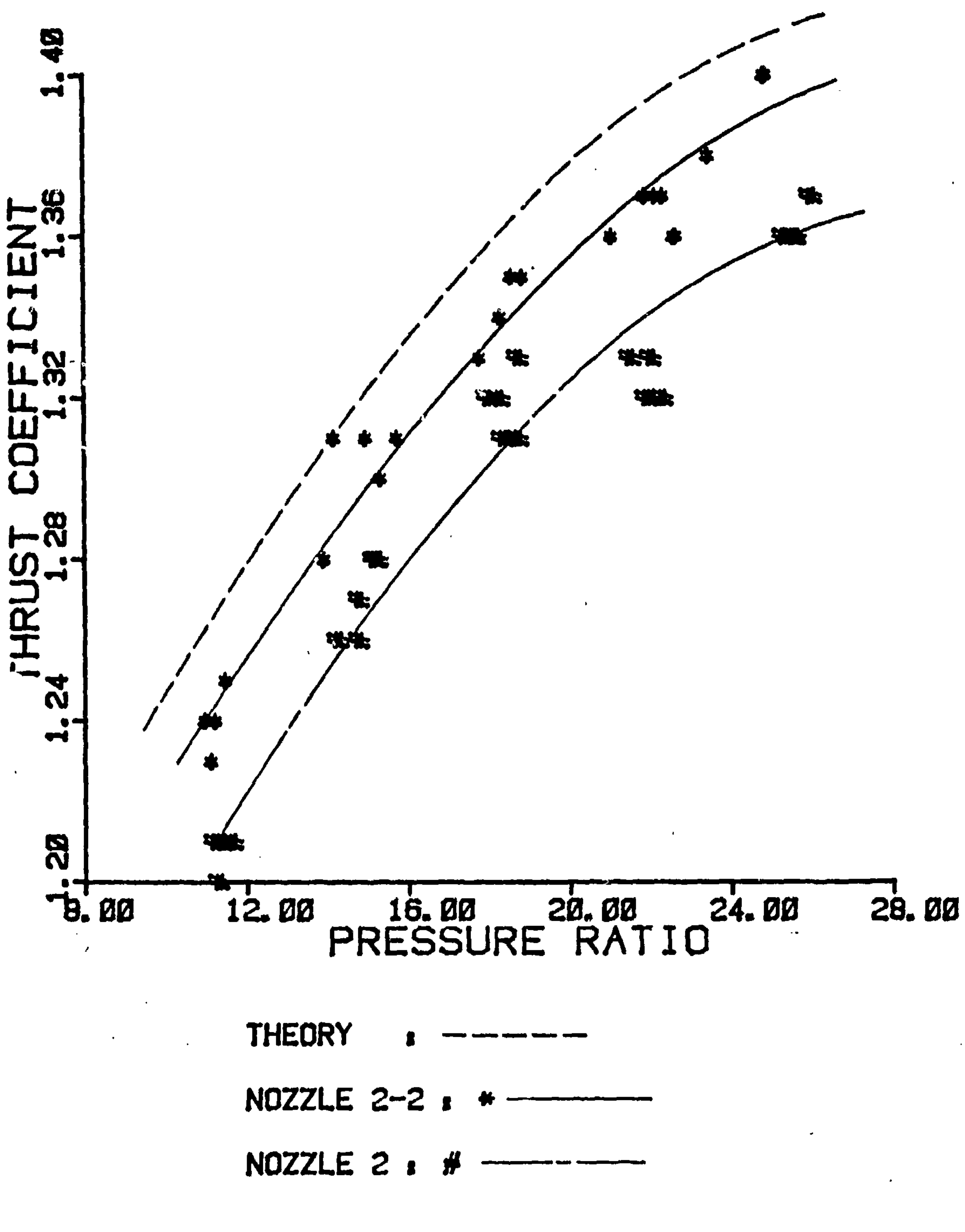


FIG A-1 : THRUST COEFFICIENT VS PRESSURE RATIO
FOR NOZZLE 2-2 & 2

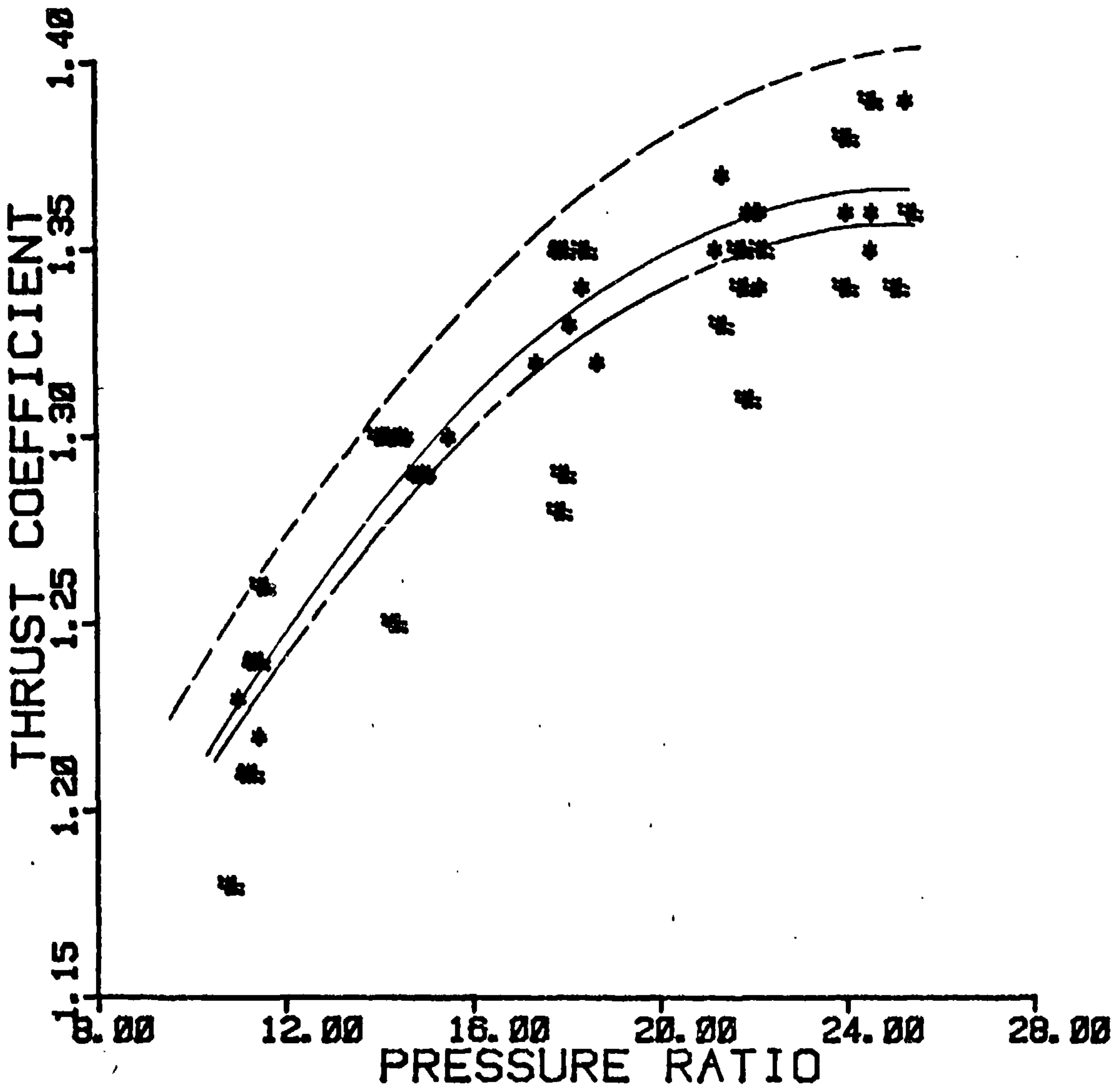


FIG A-2 : THRUST COEFFICIENT VS PRESSURE RATIO
FOR NOZZLE 3-4 & 3

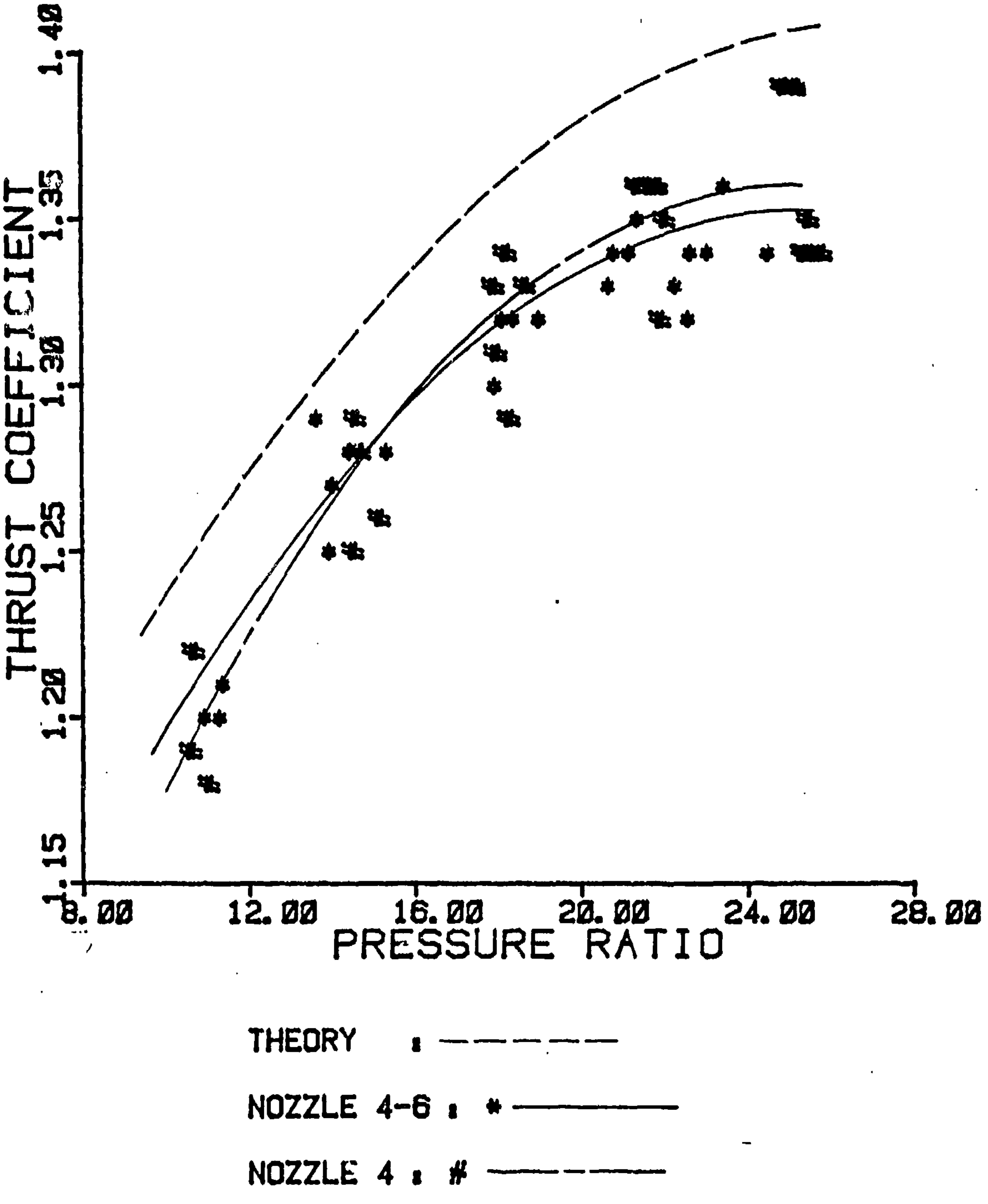


FIG A-3 : THRUST COEFFICIENT VS PRESSURE RATIO
FOR NOZZLE 4-6 & 4

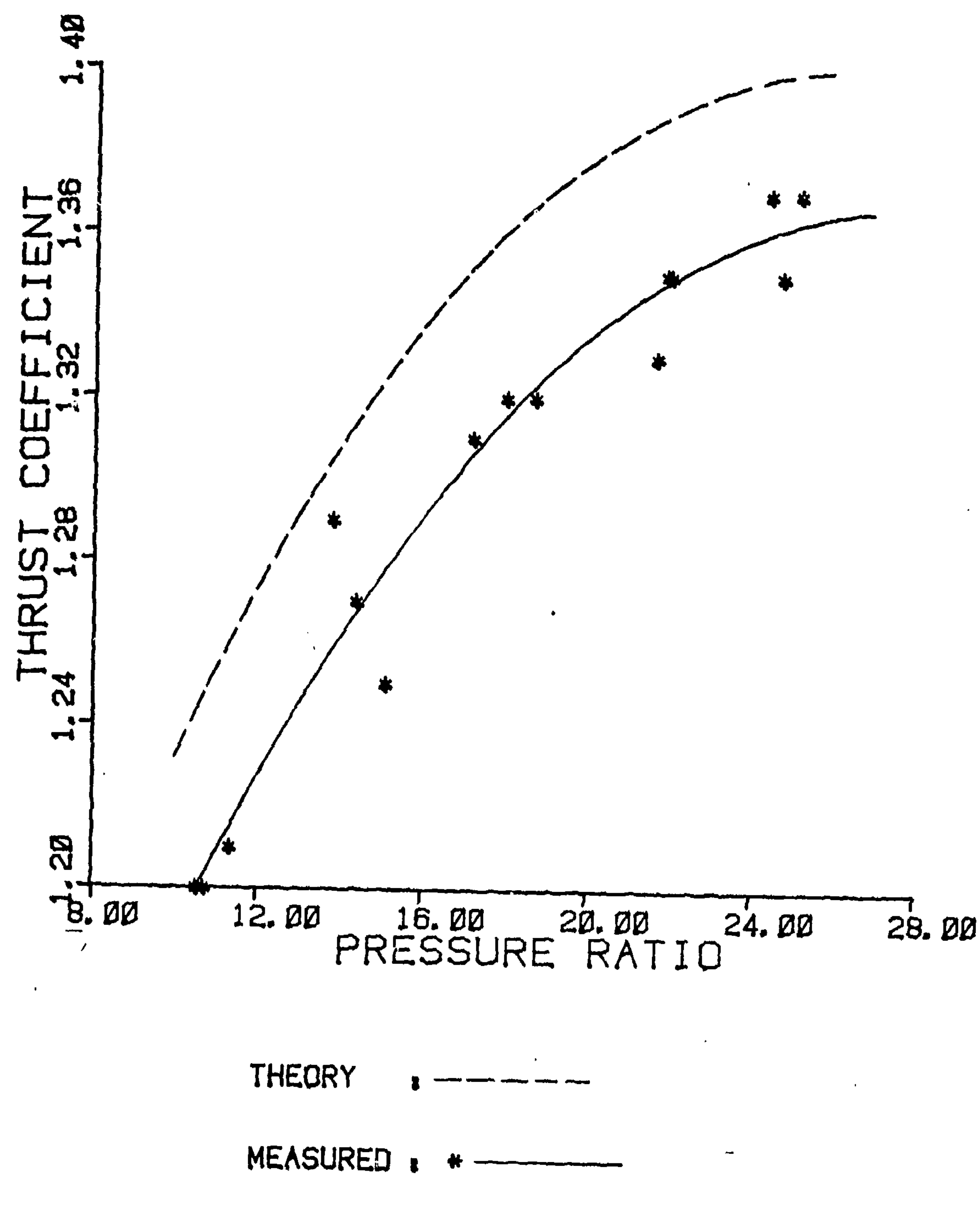


FIG A-4 : THRUST COEFFICIENT VS PRESSURE RATIO
FOR NOZZLE 1

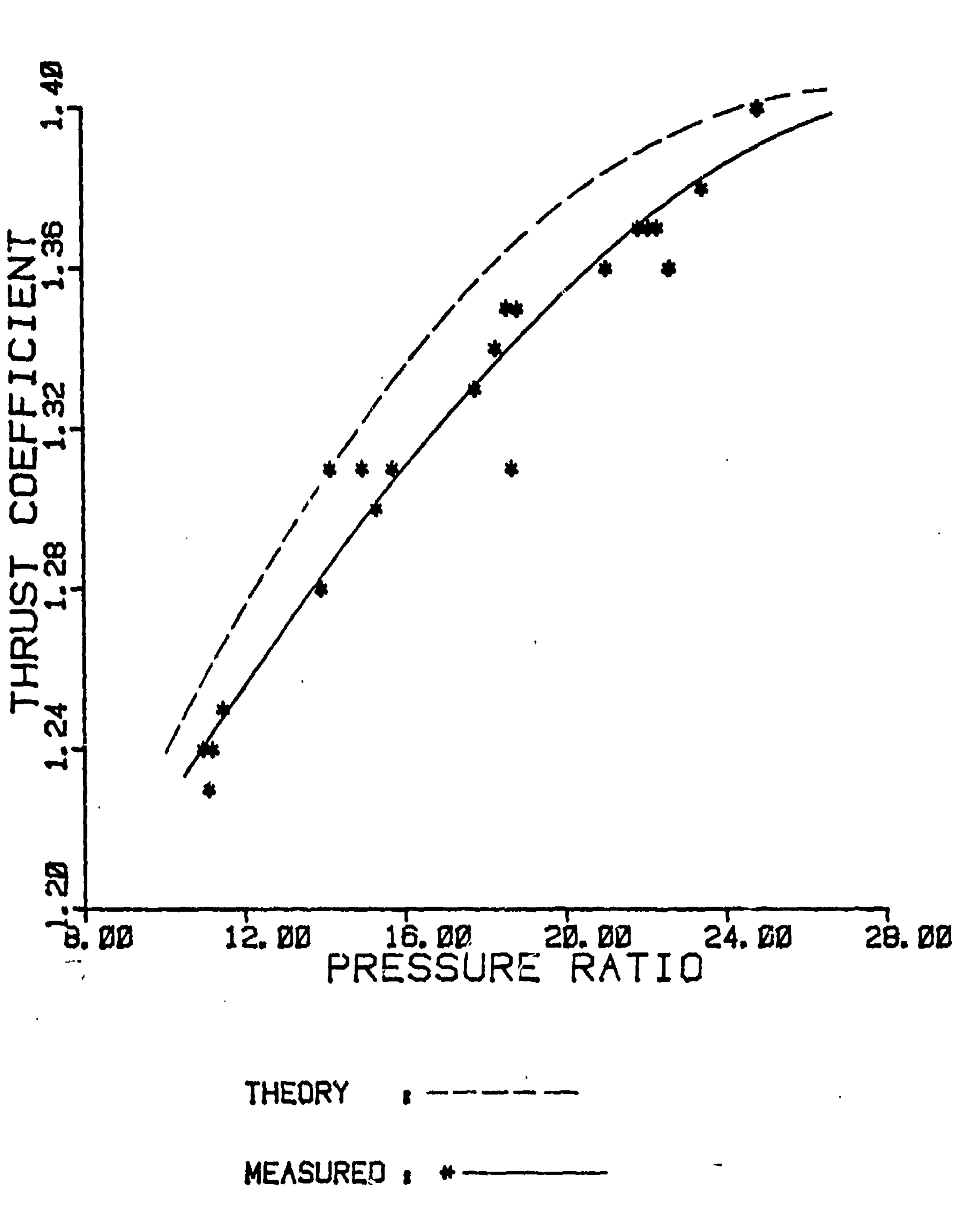


FIG A-5 : THRUST COEFFICIENT VS PRESSURE RATIO
FOR NOZZLE 2-2

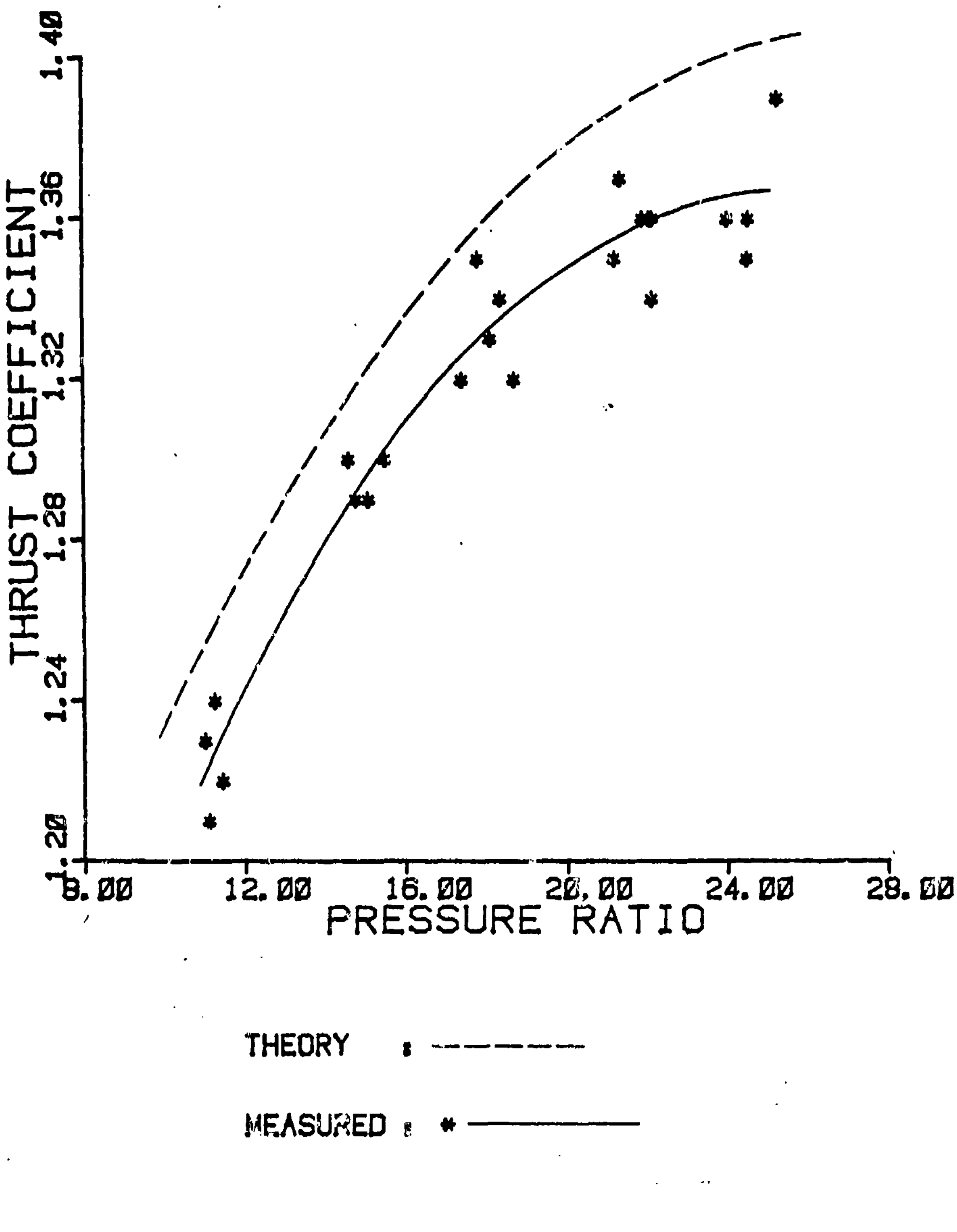


FIG A-6 : THRUST COEFFICIENT VS PRESSURE RATIO
FOR NOZZLE 3-4

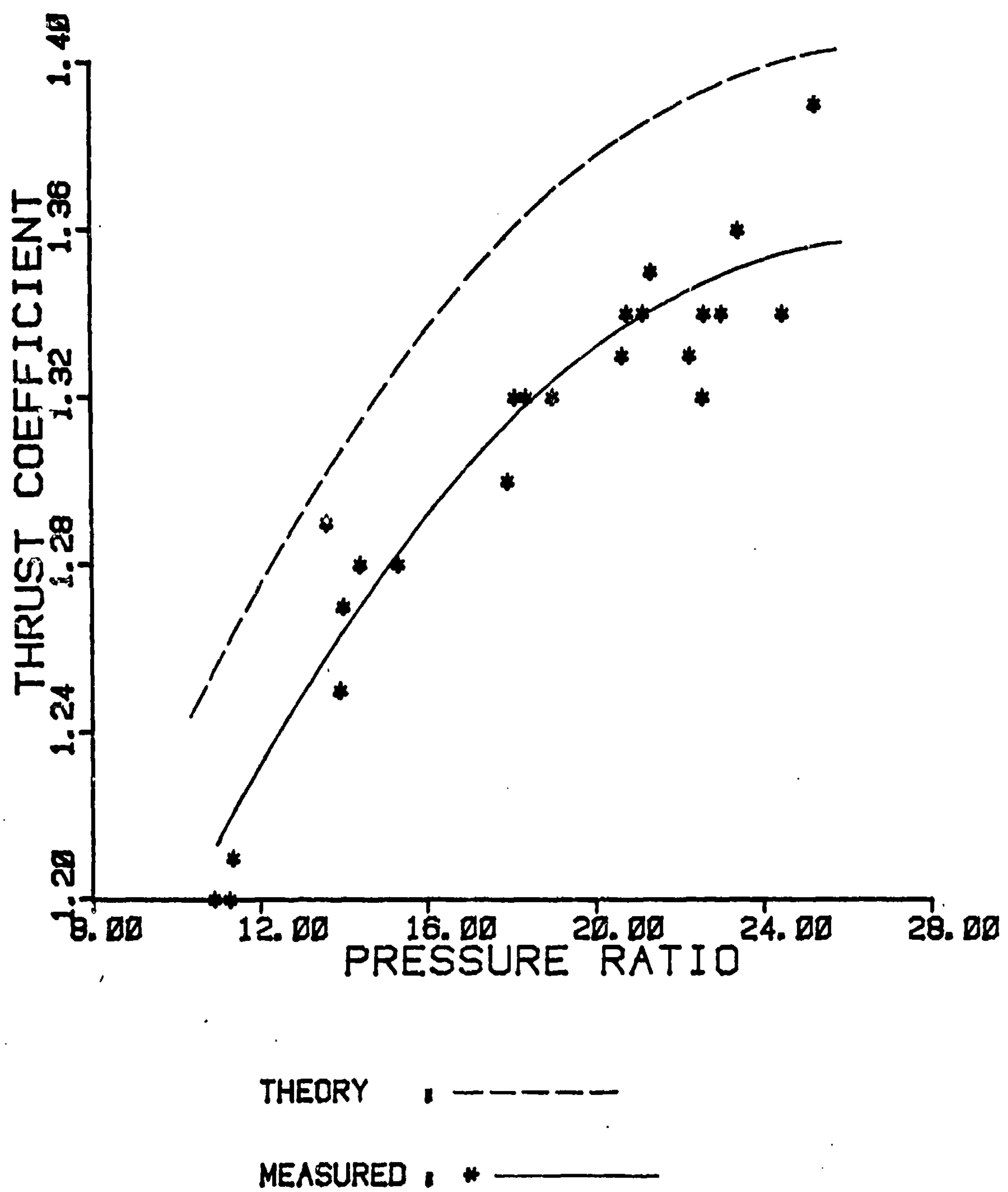
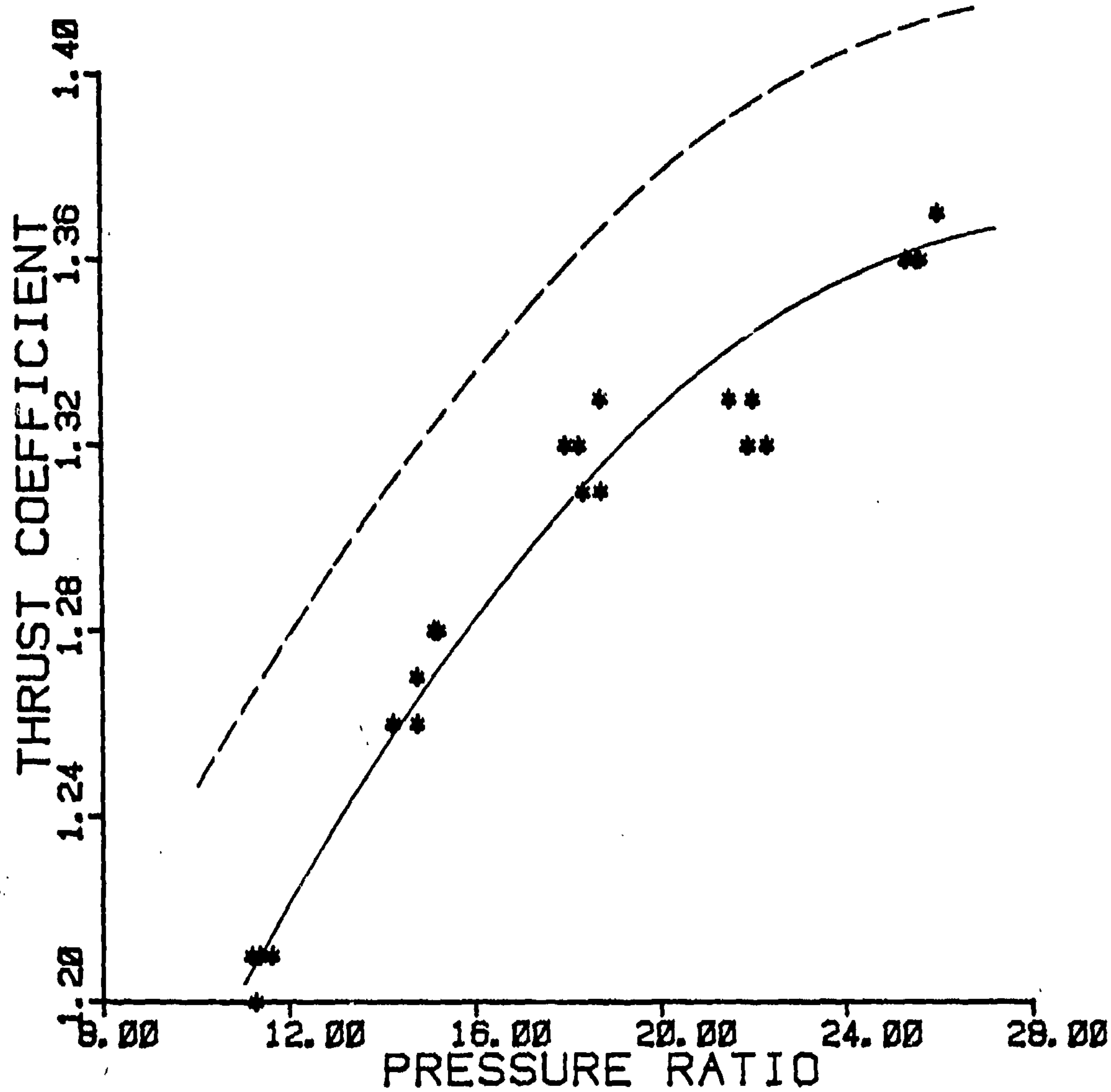


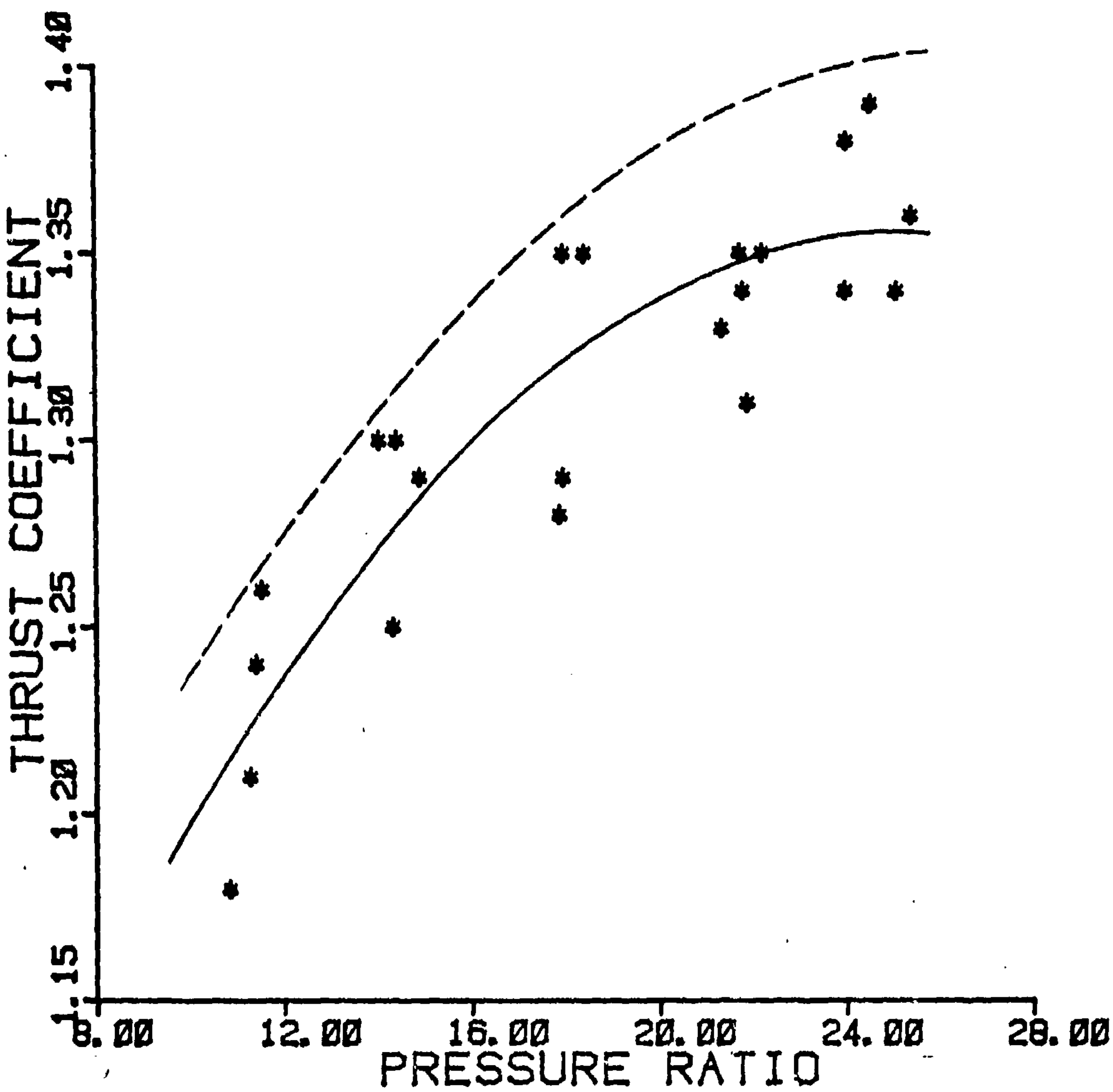
FIG A-7 : THRUST COEFFICIENT VS PRESSURE RATIO FOR NOZZLE 4-6



THEORY :

MEASURED : *

FIG A-8 : THRUST COEFFICIENT VS PRESSURE RATIO
FOR NOZZLE 2



THEORY :

MEASURED : *

FIG A-9 : THRUST COEFFICIENT VS PRESSURE RATIO FOR NOZZLE 3

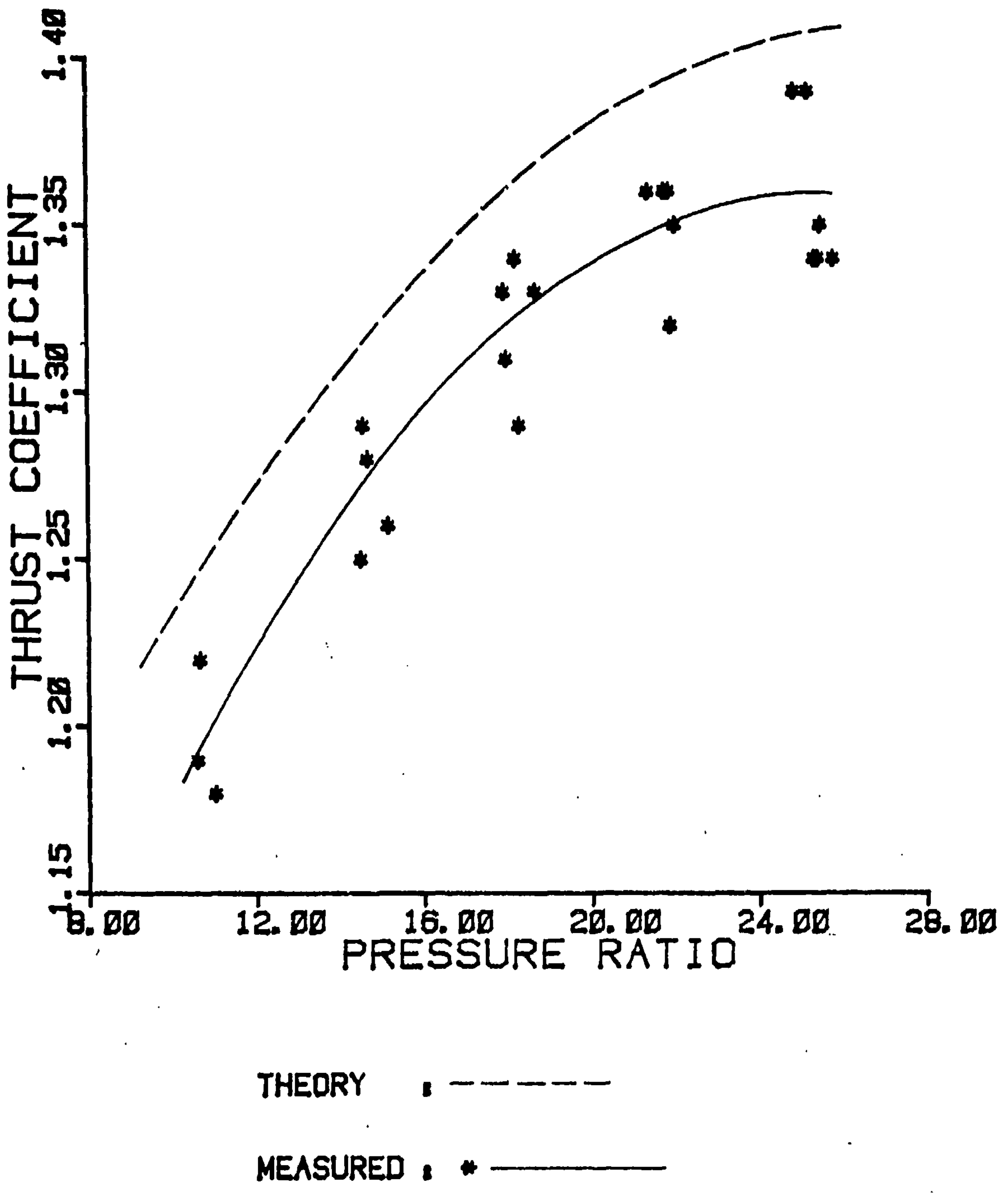


FIG A-10 : THRUST COEFFICIENT VS PRESSURE RATIO FOR NOZZLE 4

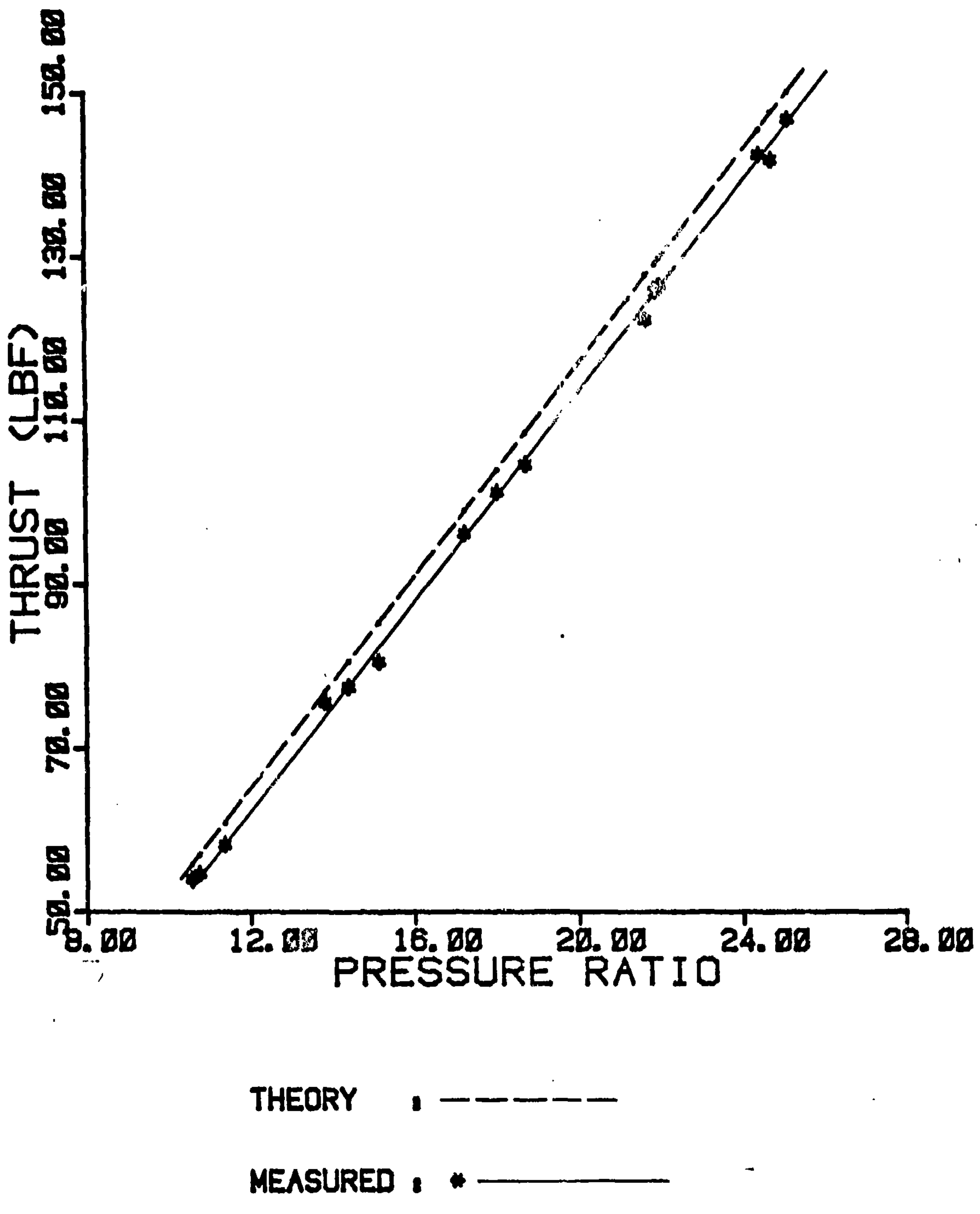


FIG A-11 : THRUST VS PRESSURE RATIO FOR NOZZLE 1

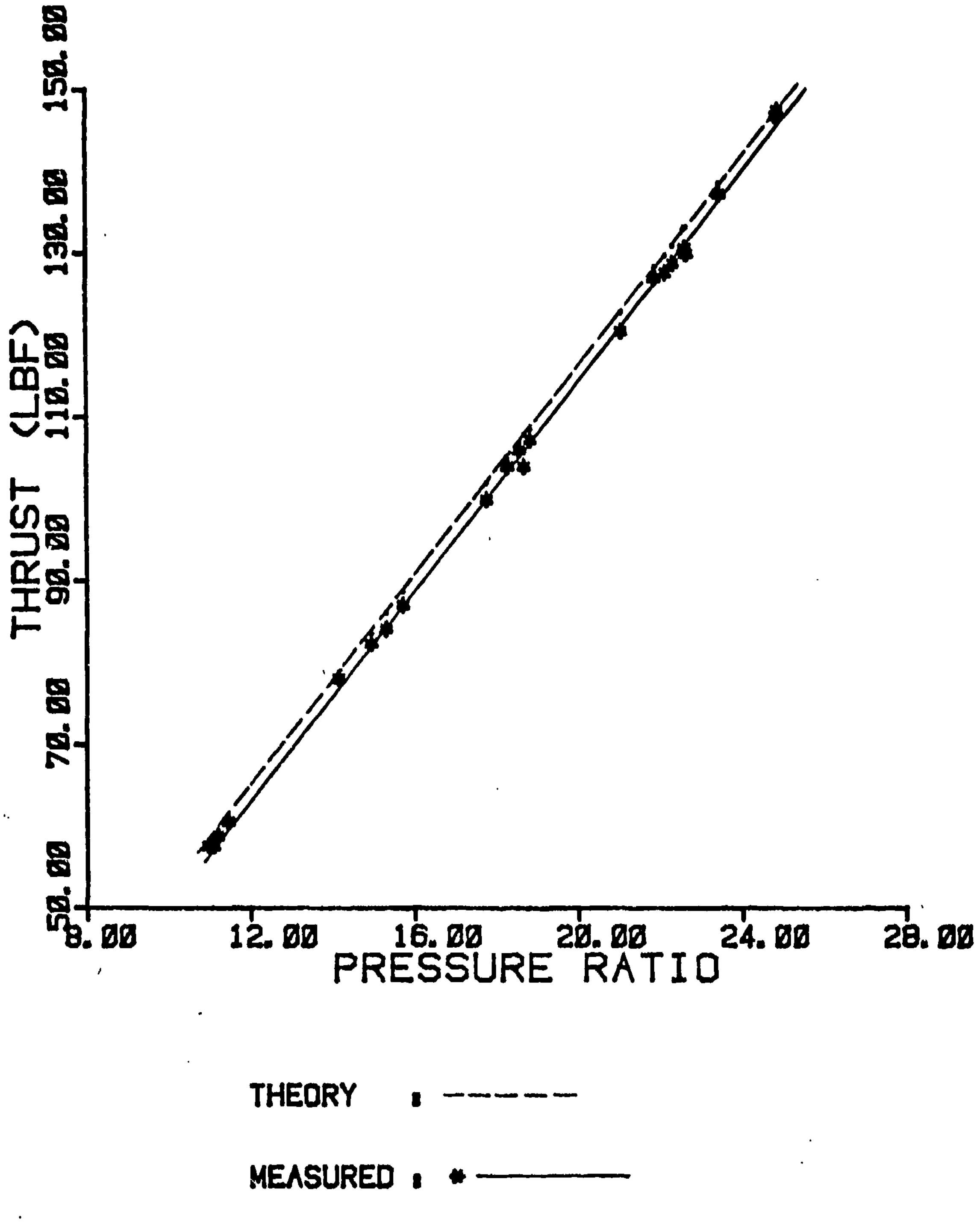
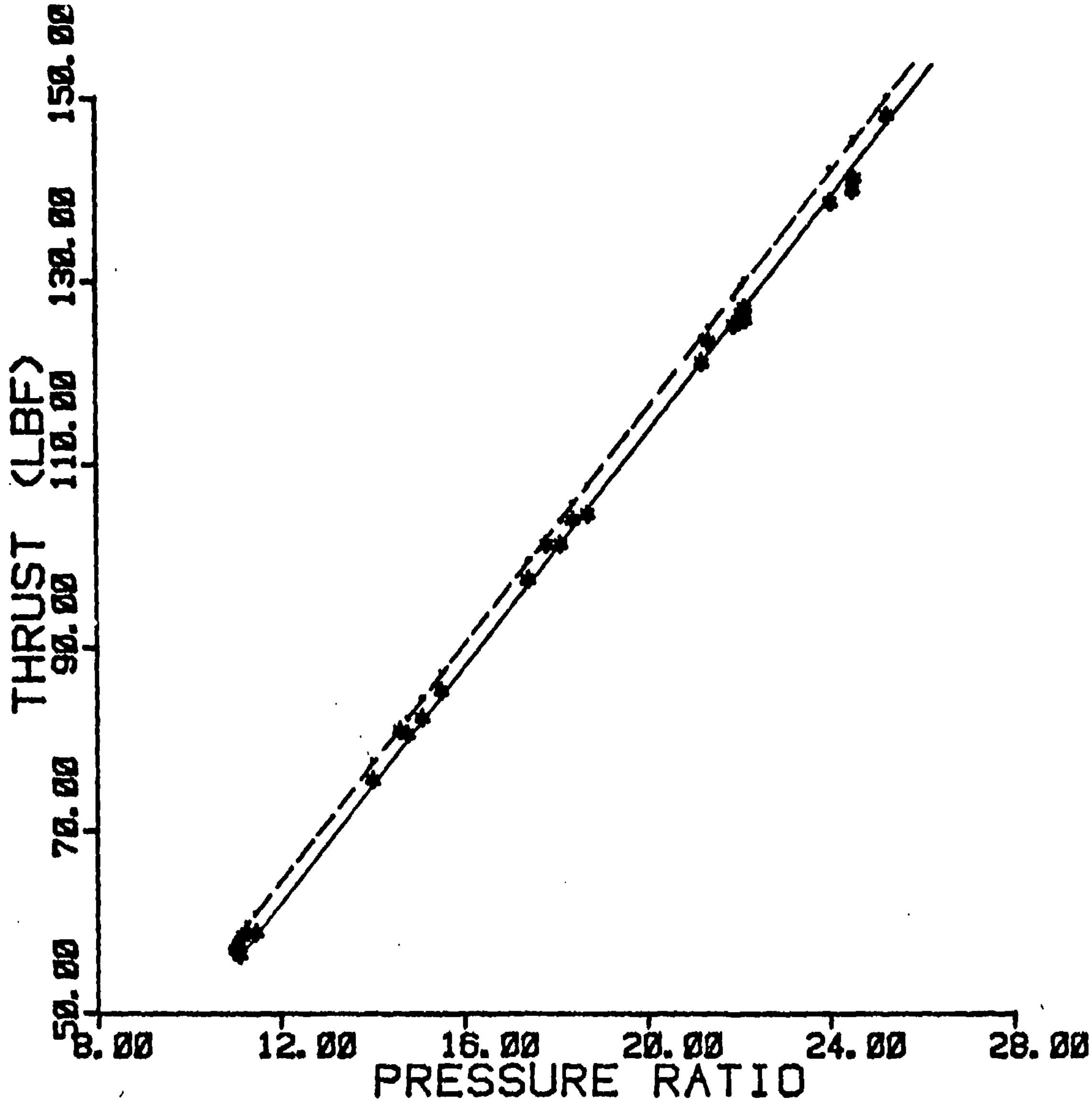


FIG A-12 : THRUST VS PRESSURE RATIO FOR NOZZLE 2-2



THEORY : ------

MEASURED : * ————

FIG A-13 : THRUST VS PRESSURE RATIO FOR NOZZLE 3-4

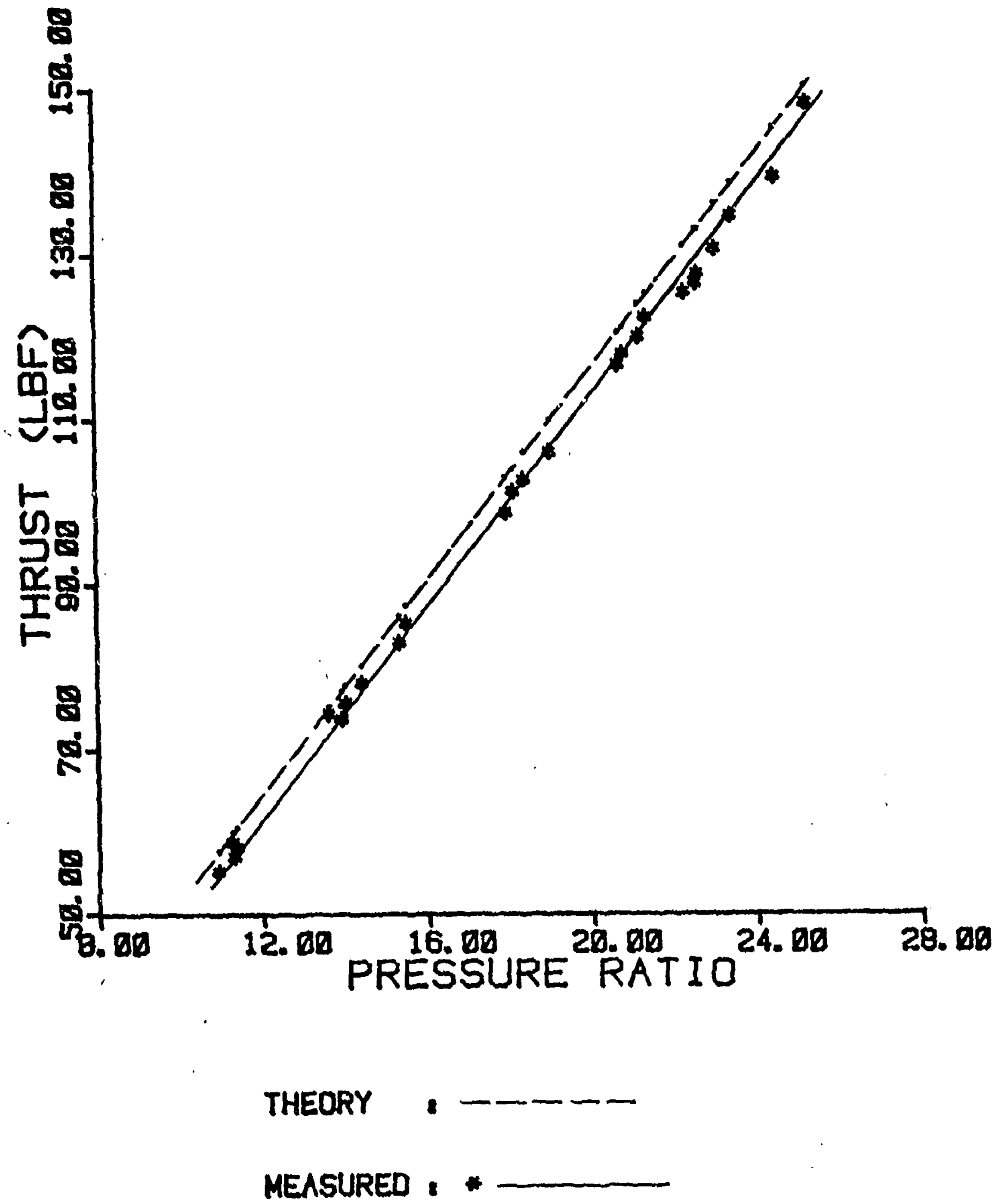
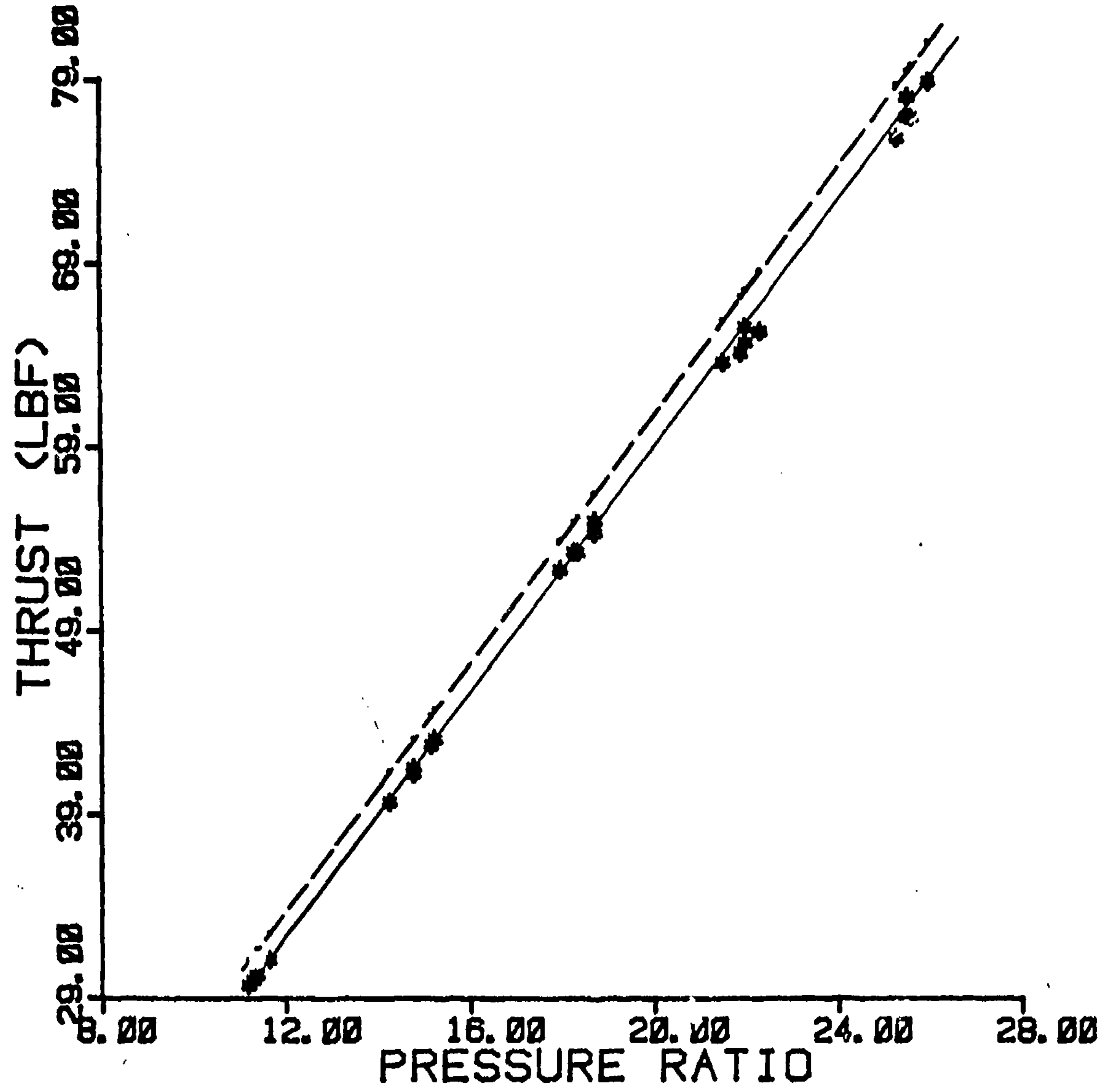


FIG A-14 : THRUST VS PRESSURE RATIO FOR NOZZLE 4-6



THEORY : ------

MEASURED : * ———

FIG A-15 : THRUST VS PRESSURE RATIO FOR NOZZLE 2

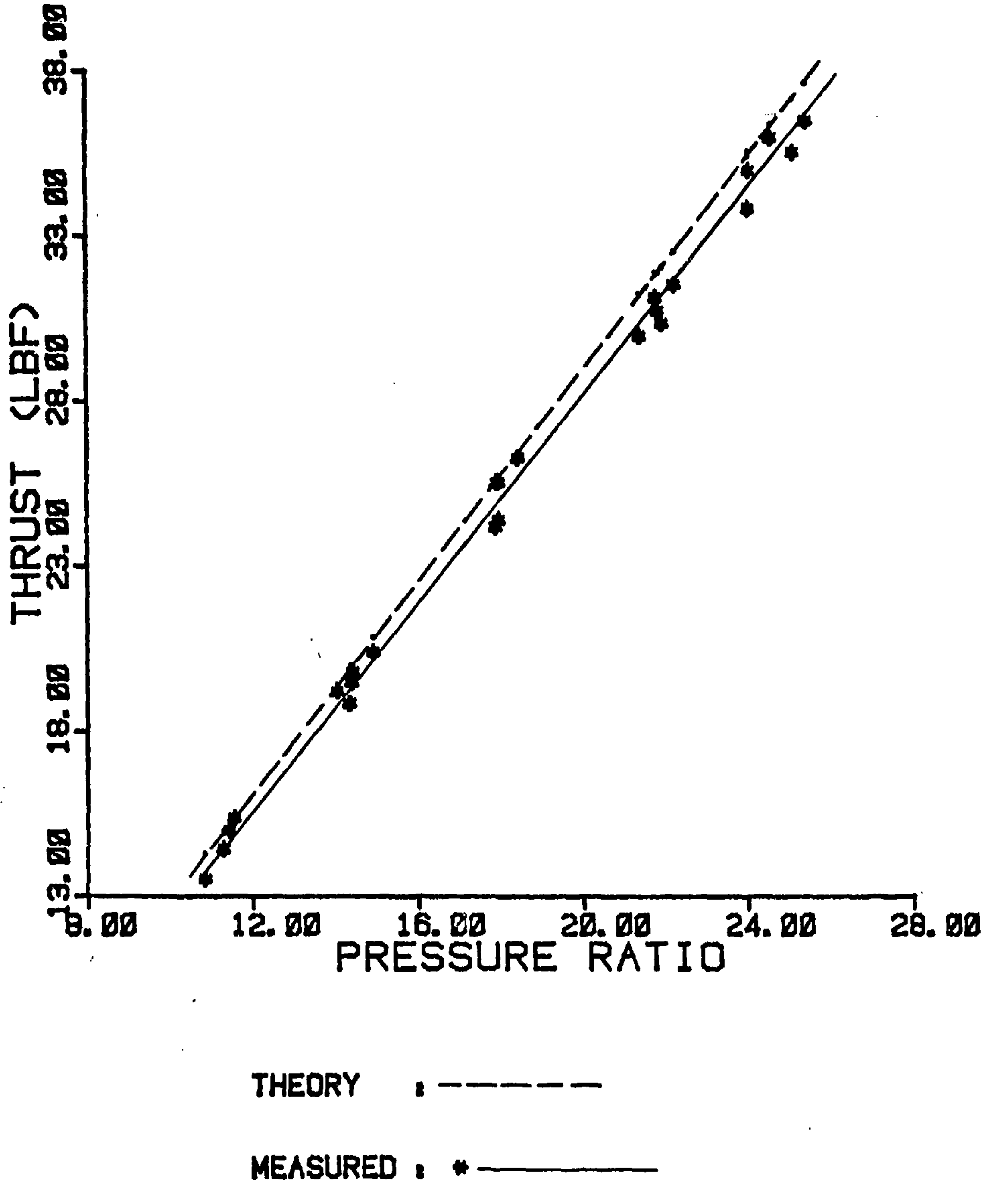
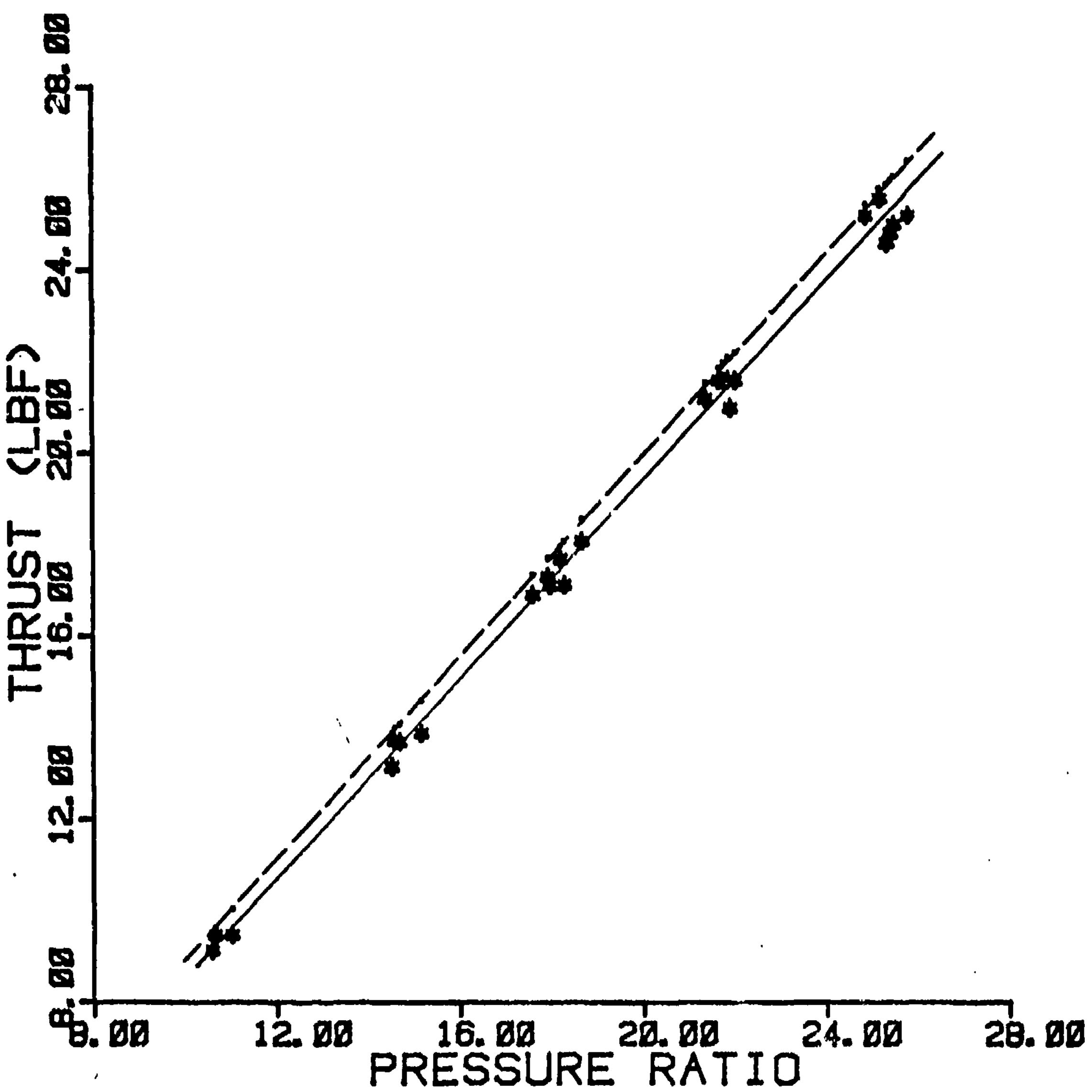


FIG A-16 : THRUST VS PRESSURE RATIO FOR NOZZLE 3



THEORY : ------

MEASURED : * ———

FIG A-17 : THRUST VS PRESSURE RATIO FOR NOZZLE 4

Table A-1 Nozzle Equations Derived by Computer for Fig A-1 thru A-17 and put into Text.

Nozzle	y =	$a(2)PR^2$ +	$a(1)PR$ +	b
2-2	C_{f_t}	-0.0006	0.0329	0.9662
	C_{f_m}	-0.0004	0.0236	1.0260
	T_t		6.45	-12.86
	T_m		6.38	-12.93
3-4	C_{f_t}	-0.0006	0.0331	0.9633
	C_{f_m}	-0.0007	0.0366	C.9103
	T_t		6.44	-12.72
	T_m		6.28	-12.24
4-6	C_{f_t}	-0.0006	0.0323	0.9738
	C_{f_m}	-0,0006	0.0319	0.9346
	T_t		6.45	-12.71
	T_m		6.23	-12.18
1	C_{f_t}	-0.0007	0.0371	0.9325
	C_{f_m}	-0.0006	0.0318	0.9291
	T_t		6.51	-13.39
	T_m		6.34	-13.48

Table 1 (continued)

Nozzle	y	=	$a(2)PR^2$	+	$a(1)PR$	+	b
2	C_{f_t}		-0.0006		0.0329		0.9662
	C_{f_m}		-0.0005		0.0296		0.9412
	T_t				3.37		-6.64
	T_m				3.29		-7.09
3	C_{f_t}		-0.0006		0.0338		0.9607
	C_{f_m}		-0.0007		0.0345		0.9242
	T_t				1.61		-3.19
	T_m				1.55		-2.85
4	C_{f_t}		-0.0006		0.0325		0.9672
	C_{f_m}		-0.0008		0.0410		0.8496
	T_t				1.11		-2.18
	T_m				1.08		-2.18

Table A-2 Averaged Theory Equations Derived by Computer and Put into Text

Fig	y	=	$a(2)PR^2$	+	$a(1)PR$	+	b
5	C_{f_t}		-0.0007		0.0351		0.9466
A-1	C_{f_t}		-0.0005		0.0298		0.9928
A-2	C_{f_t}		-0.0006		0.0318		0.9754
A-3	C_{f_t}		-0.0006		0.0335		0.9616

Appendix B

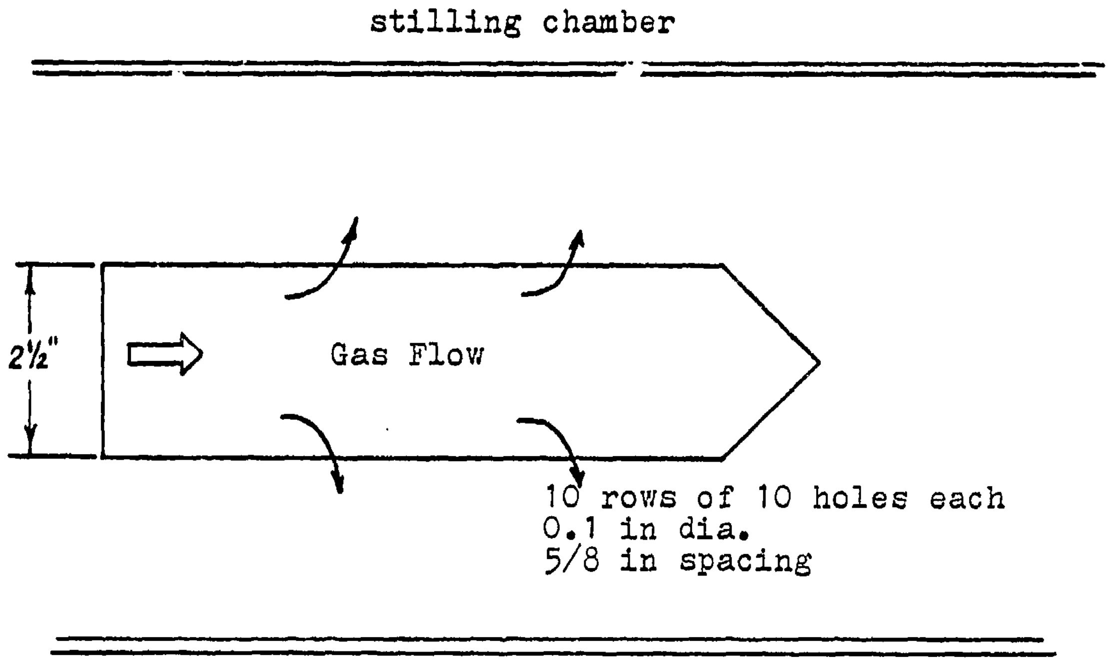


Fig B-1 Diffuser in Stilling Chamber

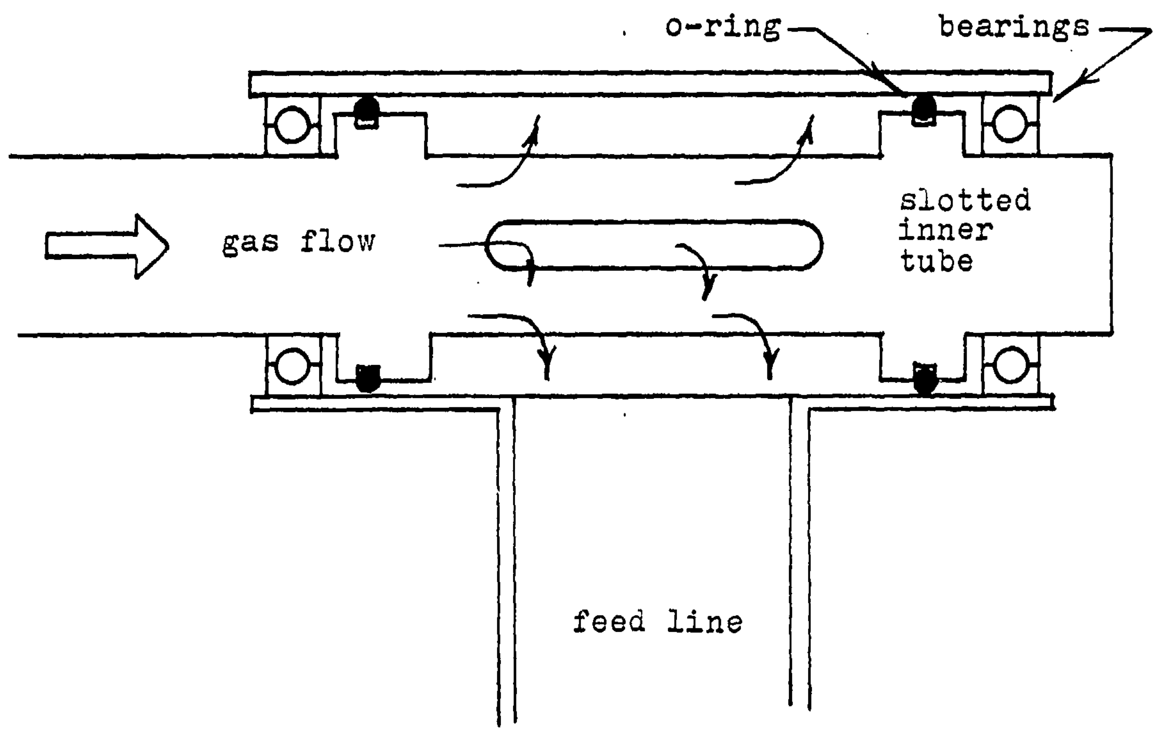


Fig B-2 Pivot Point Assembly

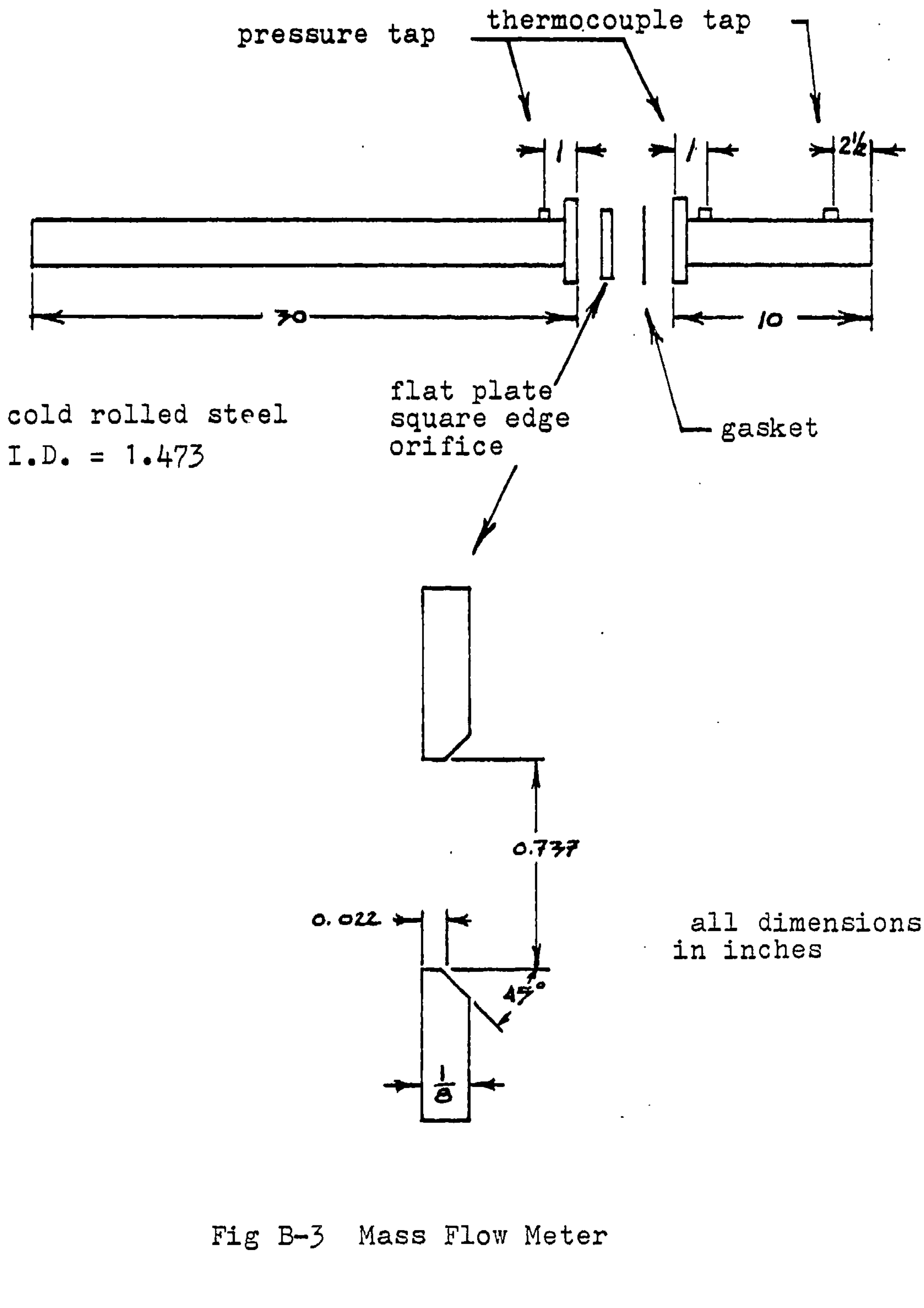


Fig B-3 Mass Flow Meter

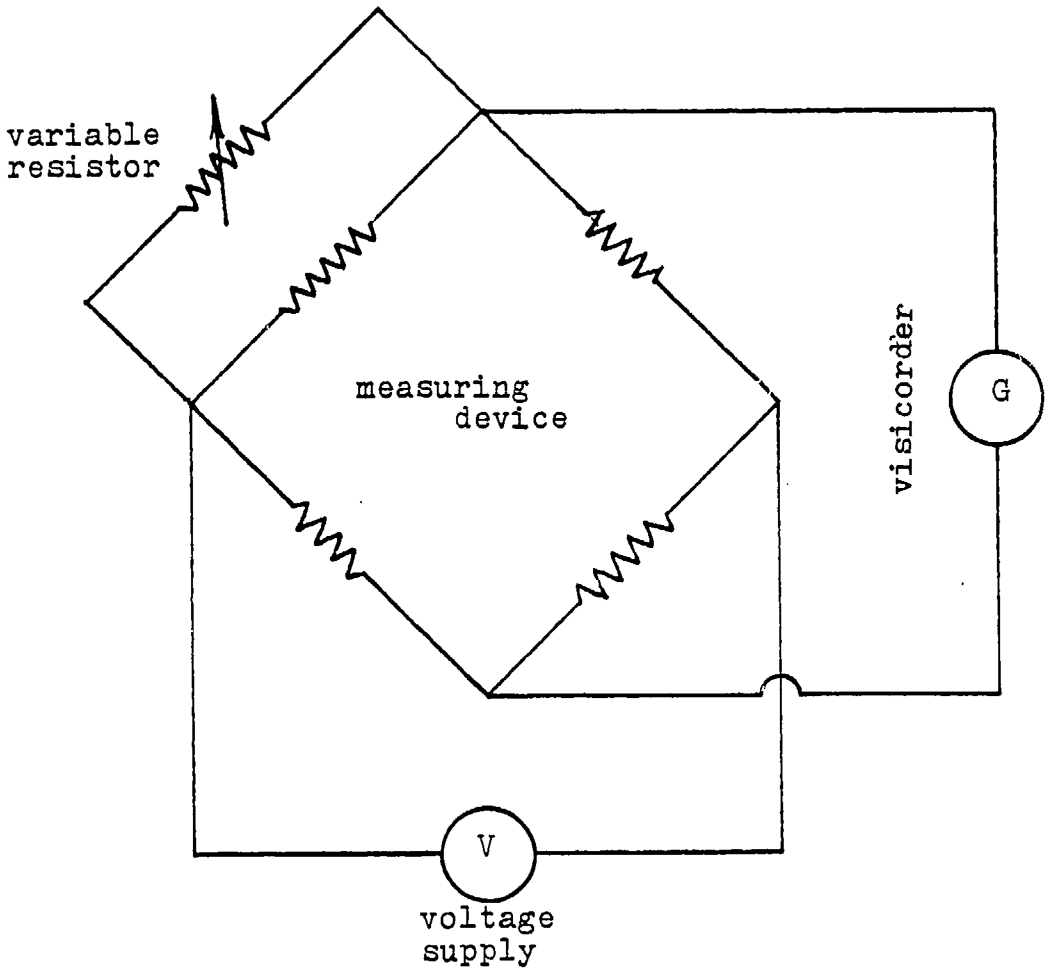


Fig B-4 Variable Resistor Setup

Appendix C

Sample Calculation

The thrust coefficient determines the amplification of thrust due to the gas expansion in the rocket nozzle as compared to the thrust that would be exerted if the chamber pressure acted over the throat area only (ref 5). The basic definition of thrust coefficient is:

$$C_f = \frac{T}{A_t p_1}$$

where: T = thrust (lb_f)

A_t = throat area (in^2)

p_1 = chamber pressure (psia)

Thrust coefficient is a non-dimensional term that is used in this study to compare the thrust performance among the 7 nozzles tested. The measured thrust coefficient was found by measuring the thrust, throat area and chamber pressure directly. To determine the theoretical thrust coefficient, more extensive calculations were carried out. To obtain the the theoretical thrust, Sutton (ref 5) used conservation of momentum to find:

$$T = \frac{\dot{m}V_2}{g_c} + (p_2 - p_3) A_2$$

where: T = thrust (lb_f)

$\dot{m}$ = mass flow rate (lb_m/s)

V_2 = exit velocity of gas (fps)

$g_c = 32.174 \dfrac{ft \cdot lb_m/s^2}{lb_f}$

p_2 = pressure at exit plane of nozzle (psia)

p_3 = ambient pressure (psia)

A_2 = nozzle exit area (in^2)

A_2 can be measured directly from the nozzle itself and p_3 is the barometric pressure during the testing period. V_2 and p_2 are found using isentropic relations from ref 2. The mass flow rate ($\dot{m}$) can be determined from two methods.

Method I : Mass Flow Meter

The following equations were obtained from ref 1 (p58) and were derived from the energy equation.

$D = 1.473''$ $\qquad$ $d = 0.737''$

$\beta = d/D = 0.500$

$K_e = 0.5993 + 0.007/D + (0.364 + 0.076\sqrt{D})$

$K_e = 0.6308$

$A = d(830 - 5000\beta + 9000\beta^2 - 4200\beta^3 + 530/\sqrt{D})$

$A = 362.59$

$K_o = K_e(d*10^6/(d*10^6 + 15A))$

$K_o = 0.6262$

$$K = C/\sqrt{(1 - \beta^4)} = K_o(1 + A/R_d)$$

$$R_d = 48\dot{m}/(\pi d \mu)$$

where: $\dot{m} = 1.37\ lb_m/s$ (assumed)

$\mu = 1.19925\ 10^5\ lb_m/ft\ s$

$$R_d = 2.3\ 10^6$$

$$K = 0.6262$$

then:

$$\dot{m} = \pi/4 * d^2 * K * \sqrt{(2 g_c \rho_a (p_a - p_b))}$$

$$\rho_a = p_a/(z\ R\ T_a)$$

where: z = compressibility factor

$= 0.99$ @ $p_a = 350$ psia $T_a = 70F$

R = gas constant

$= 55.35\ lb_f\ ft/(R\ lb_m)$

substituting:

$$\dot{m} = 0.2895\sqrt{(p_a/T_a)(p_a - p_b)} \qquad lb_m/s$$

where: p_a = pressure before orifice (psia)

p_b = pressure after orifice (psia)

T_a = temperature of gas (R)

Method II : Isentropic Flow

$$\dot{m} = \rho_t A_t V_t$$

for choked flow M = 1

ref 2 $\quad T_t = 0.8333\ T_1$

$$p_t = 0.528282\ p_1$$

$$V_t = M_t * a_t$$

where: $M_t = 1.0$

$$a_t = \sqrt{g_c \gamma R T_t}$$

$$\rho_t = p_t/(RT_t)$$

where: $R = 53.35\ lb_f\ ft/(R\ lb_m)$

substituting:

$$\dot{m} = 0.522\ (p_1\ A_t/T_1) \quad lb_m/s$$

where: p_1 = chamber pressure (psia)

T_1 = chamber temperature (R)

A_t = throat area (in^2)

Continuing with the thrust equation:

$$V_2 = M_2\ a$$

where: M_2 = exit mach number

$$a = \sqrt{g_c \gamma R T_2} \quad \text{fps}$$

from ref 2:

$A/A^* = 3.000$ given area ratio

then: $T_2 = T_1\ (0.418275)$ R

$M_2 = 2.637$

$p_2 = p_1\ (0.047329)$ psia

$\gamma = 1.4$

$$g_c = 32.174\ \frac{lb_m\ ft}{lb_f\ s^2}$$

$R = 53.35\ lb_f\ ft/(R\ lb_m)$

substituting:

$V_2 = 85.1562\sqrt{T_1}$ fps

where: T_1 = chamber temperature R

The ambient pressure, p_3, is measured in Hg. To convert to psia:

$p_3 = p_a\ (0.4898)$ psia

A_2 is measured directly from the nozzle exit.

$A_2 = \pi/4 * d^2$ in^2

The exit areas were as follows:

1	0.8882759 in^2		
2	0.4624008 in^2	2-2	0.8835211 in^2
3	0.2206246 in^2	3-4	0.8824986 in^2
4	0.1520122 in^2	4-6	0.8835729 in^2

The thrust can now be calculated for an assumed p_1 and T_1. It is assumed that the temperature measurement is reasomably correct and can be used for the theoretical calculation. Temperature of the gas was measured in degree F. When converted to absolute temperature and the square root is taken, a temperature uncertainty of $\pm$ 1.0F has little effect in the theoretical calculation.

Also it should be noted that optimum expansion takes place when $p_2 = p_3$. This occurs when:

$$\frac{p_1}{p_3} = 1/0.047329$$

or $$P_r = 21.129$$

The theoretical and measured thrust coefficients can now be determined:

$$C_{f_t} = \frac{T_t}{A_t p_1} \qquad C_{f_m} = \frac{T_m}{A_t p_1}$$

Error Analysis

In measuring the data, the visicorder could give the following resolutions in its recordings:

$$p_1 = 150 \pm 1.25 \text{ psig}$$

$$T = 10 \pm 0.175 \text{ lb}_f \text{ for nozzles 3 \& 4}$$

$$= 35 \pm 0.28 \text{ lb}_f \text{ for nozzle 2}$$

$$= 60 \pm 0.59 \text{ lb}_f \text{ for nozzles 1, 2-2, 3-4, \& 4-6}$$

In measuring the throat areas, the diameters could be measured to within $\pm$ 0.0001 in.

$$A_t = 0.0507 \pm 0.00016 \text{ in}^2 \text{ for nozzle 4}$$

$$= 0.1541 \pm 0.00028 \text{ in}^2 \text{ for nozzle 2}$$

$$= 0.2961 \pm 0.00037 \text{ in}^2 \text{ for nozzle 1}$$

Given: $C_f = \frac{T}{A_t p_1}$

then: $\frac{\partial C_f}{\partial T} = \frac{1}{A_t p_1}$

$$\frac{\partial C_f}{p_1} = \frac{T}{A_t} \left(-\frac{1}{p_1}\right)^2$$

$$\frac{\partial C_f}{\partial A_t} = \frac{T}{p_1} \left(-\frac{1}{A_t}\right)^2$$

then: $$\epsilon = \pm \sqrt{\left(\frac{\partial C_f}{\partial T}\epsilon_T\right)^2 + \left(\frac{\partial C_f}{\partial p_1}\epsilon_{p_1}\right)^2 + \left(\frac{\partial C_f}{\partial A_t}\epsilon_{A_t}\right)^2}$$

$$\epsilon_4 = \pm \left[\left(\frac{0.175}{150*0.0507}\right)^2 + \left(\frac{10*1.25}{0.0507*150^2}\right)^2 + \left(\frac{10*0.00016}{150*0.0507^2}\right)^2\right]^{1/2}$$

$$\epsilon_4 = 0.026$$

Therefore: $C_f = C_f \pm 0.026$ for nozzle 3 & 4

Similarly: $C_f = C_f \pm 0.018$ for nozzle 2

$C_f = C_f \pm 0.017$ for nozzle 1, 2-2, 3-4, & 4-6

From this error analysis, a region within each data point may be drawn to indicate a region of uncertainty. All of the data points for each graph were used in order to fit the best curve. In comparing the data point's region of uncertainty to its vicinity to the curve, the data points indi- a high degree of repeatability from which trends may be shown in the nozzle's thrust performance.

Vita

David Hibson was born April 28, 1956 in New Haven, Conn. On March 26, 1974 he enlisted in the United States Air Force. On June 17, 1974 he graduated from Shrewsbury High School, Shrewsbury, Mass. David was discharged from the Air Force on August 25, 1977 and then entered Stevens Institute of Technology, Hoboken, New Jersey on September 2, 1977. He then entered Officer Training School on May 19, 1980 and graduated with B.E. from Stevens Institute on May 22, 1980. David then graduated from OTS and entered AFIT on August 15, 1980.

Thesis typed by--Erlene K Wenrick

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This is an experimental evaluation of the thrust performance of 3 sets of clustered, three-dimensional, converging-diverging, cold flow supersonic nozzles.A cluster of 2, 4, and 6 nozzles were designed and fabricated. Each cluster assembly has the same geometry in that their area ratio, expansion ratio, and total throat area is the same. A single nozzle with the same geometry and total throat area was used to evaluate the creditability of the testing procedure and the performance of the 3 sets of clustered nozzles. The thrust

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered) performance of each nozzle cluster was evaluated by comparison of the measured thrust coefficient of the cluster to that of a single nozzle. The nozzle with the highest thrust coefficient was the cluster of 2 nozzles. Its performance was closely followed by the cluster of 4 nozzles. The nozzle with the lowest thrust coefficient was the cluster of 6 nozzles. The results of this study indicate that the clustering of nozzles improves the thrust performance.